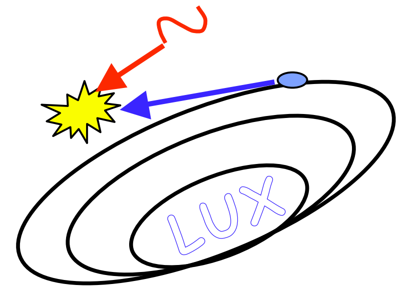


LUX - Linac-based Ultrafast X-ray source

Machine Design

BESAC sub-committee

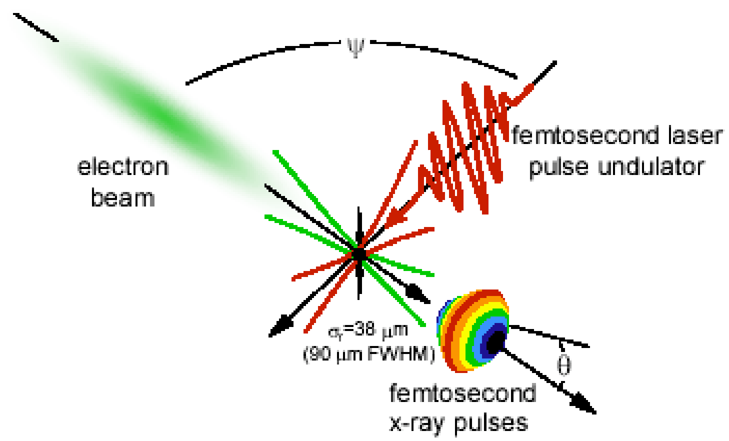
February 2003

We propose a feasible machine design which is driven by scientific requirements

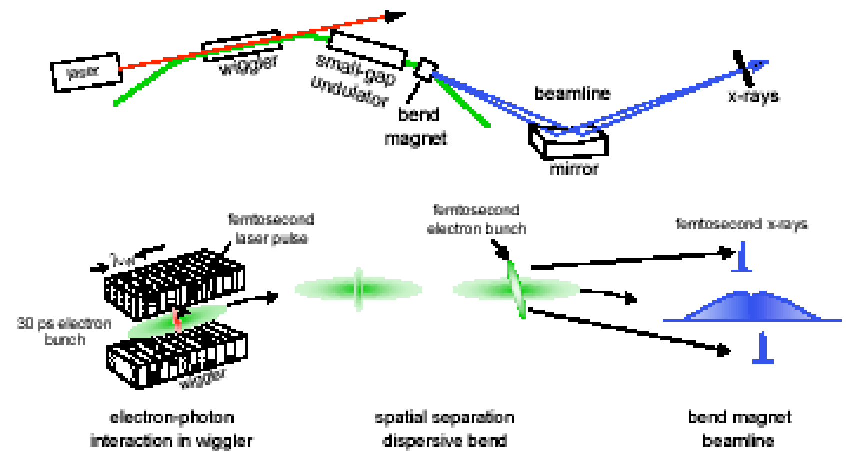
- Repetition rate — 10 kHz
- Synchronization — 10's fs
- Variable polarization
- Broad photon range — ~ 0.02-12 keV
  - Hard x-rays
    - Tunable — 1-12 keV
    - Pulse duration — ≤ 50 fs above 3 keV
    - High flux — initial 10^6, goal 10^7 (ph/pulse/0.1%BW)
  - Soft x-rays
    - Tunable — ~ 20-1000 eV
    - Pulse duration — 50-200 fs from HGHG, goal 20 fs
    - Variable flux — 10^8-10^{13} (ph/pulse/0.1%BW)

- Multiple sophisticated short-pulse lasers with temporal and spatial pulse shaping
    - 800 nm, < 100 fs oscillator serves as master oscillator
    - 267 nm photocathode laser
    - 200-150 nm tuneable HGHG seed
    - Multiple tuneable 267-3000 nm experiment initiation

LUX is the latest development in LBNL's history of ultrafast x-ray facilities



Thomson scattering

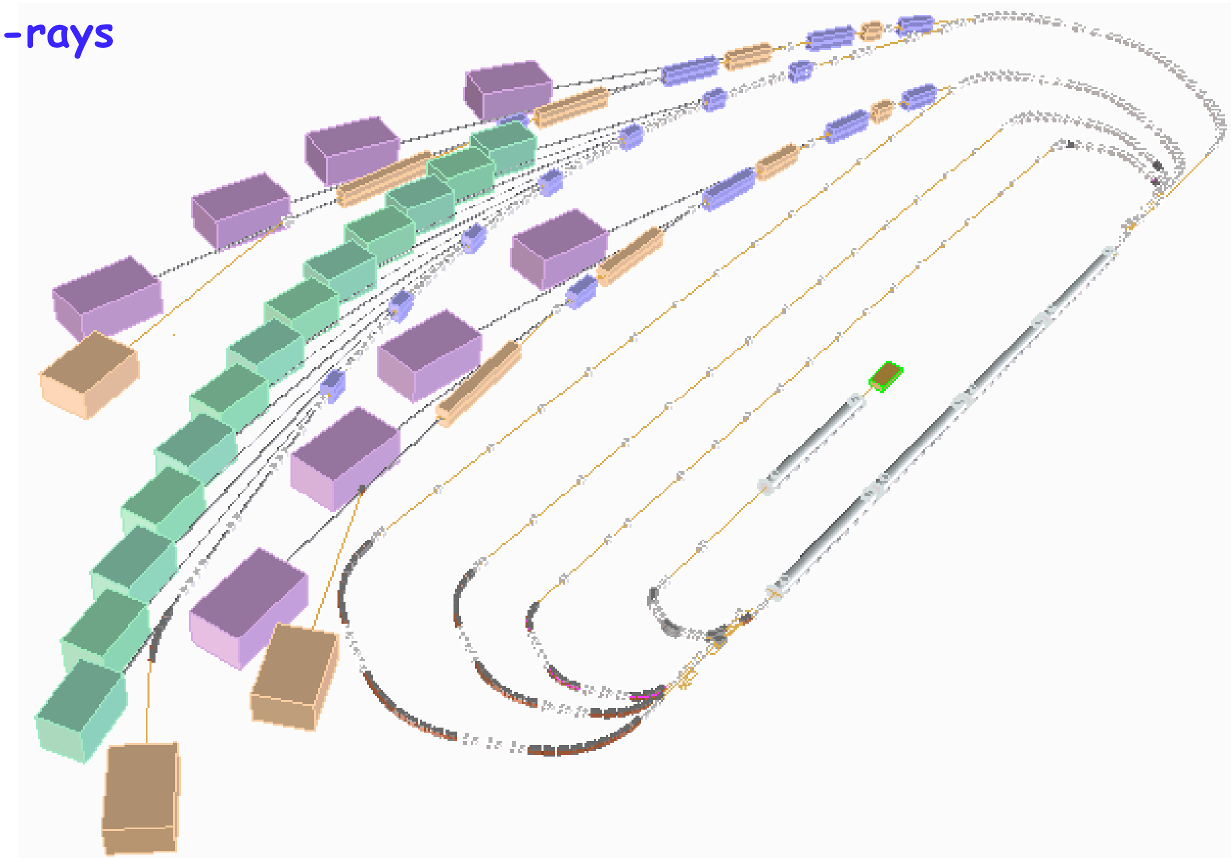


Laser slicing

- Kim, K.-J., S. Chattopadhyay, and C.V. Shank, "Generation of femtosecond x-ray pulses by 90 degree Thomson scattering", Nuc. Inst. and Meth. in Phys. Res. A, 1994. 341: p. 351-354.
- Zholents, A.A. and M.S. Zolotorev, "Femtosecond x-ray pulses of synchrotron radiation", Phys. Rev. Lett., 1996. 76(6): p. 912-915.
- Leemans, W.P., et al.," X-ray based time resolved electron beam characterization via 90° Thomson scattering", Phys. Rev. Lett., 1996. 77(20): p. 4182-4185.
- Schoenlein, R.W., et al., "Femtosecond x-ray pulses at 0.4 angstroms generated by 90° Thomson scattering: A tool for probing the structural dynamics of materials.",Science, 1996. 274: p. 236-238.
- Zholents, A., P. Heimann, M. Zolotorev, and J. Byrd, "Generation of subpicosecond x-ray pulses using RF orbit deflection", Nuc. Instr.and Methods in Phys. Res. A, 1999. 425: p. 385-389.
- Schoenlein, R.W., et al.," Generation of x-ray pulses via laser-electron beam interaction", Appl. Phys. B, 2000. 71: p. 1-10.
- Schoenlein, R.W., et al.," Generation of femtosecond pulses of synchrotron radiation", Science, 2000. 287: p. 2237-2240.

Recirculating linac concept - a refined source for ultrafast x-ray pulses

- High brightness RF photocathode gun produces high-quality electron beam
- Accelerate in multiple passes through superconducting linac
- 2.5-3 GeV beam generates x-rays



- Compact
- Highly stable superconducting rf
- Flexible configuration
  - Each pass provides opportunities for
    - manipulation of the electron beam
    - photon production
    - timing pulses
  - Variable repetition rate

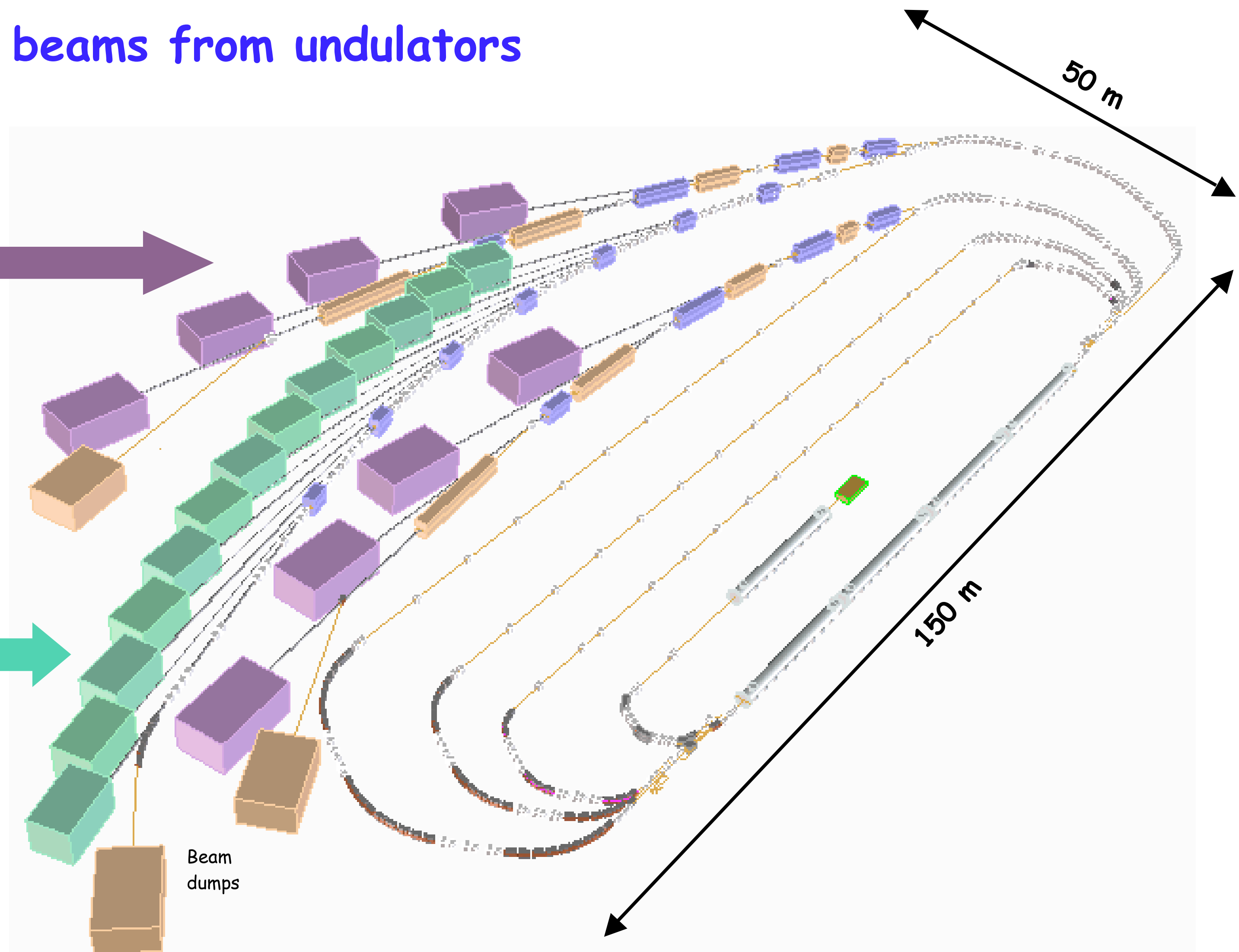
- Design is based on existing technologies and demonstrated physics parameters

Facility provides a wide range of x-ray wavelengths, operating simultaneously

- Tuneable x-ray beams from undulators

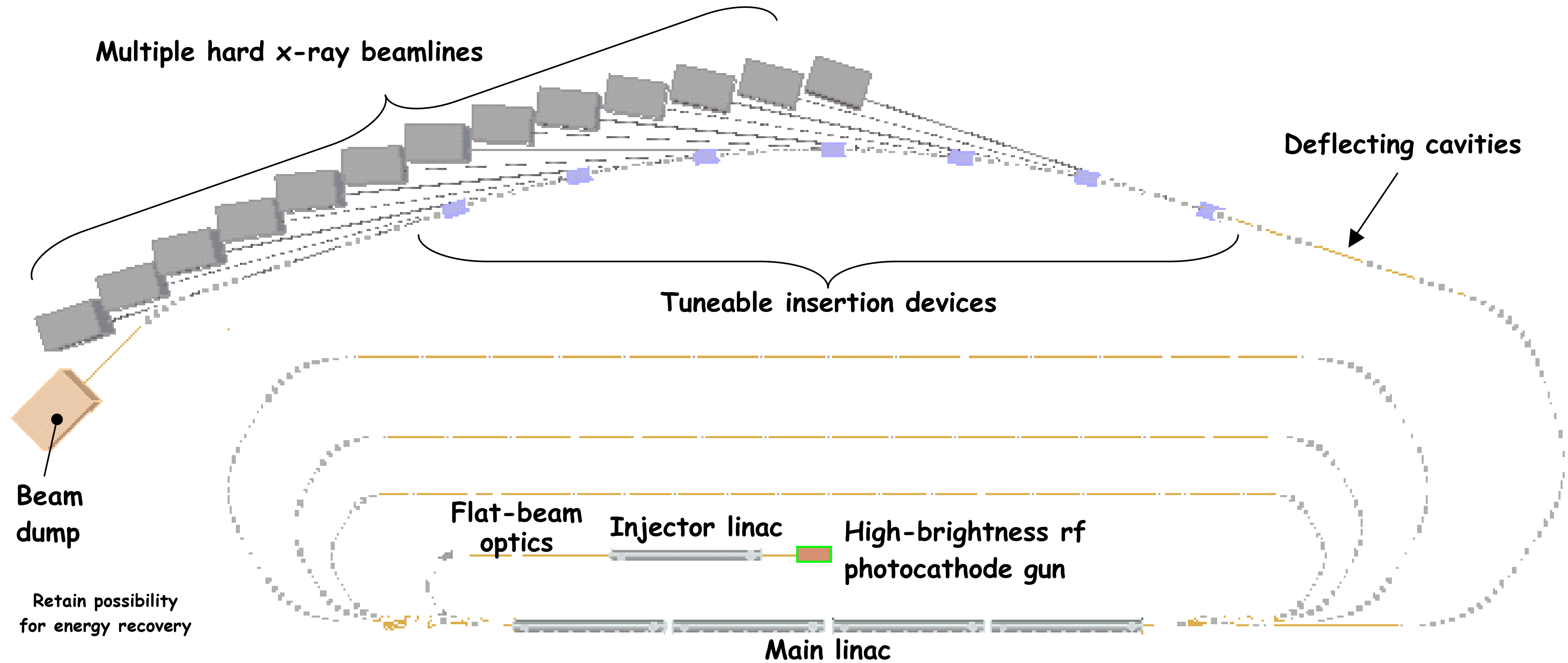
- Soft x-rays
- Seeded high-gain harmonic-generation (HGHG)
  - 20-1000 eV

- Hard x-rays
- Spontaneous emission in narrow-gap short-period insertion devices
  - 1-12 keV



Retain possibility for energy recovery by building the final arc

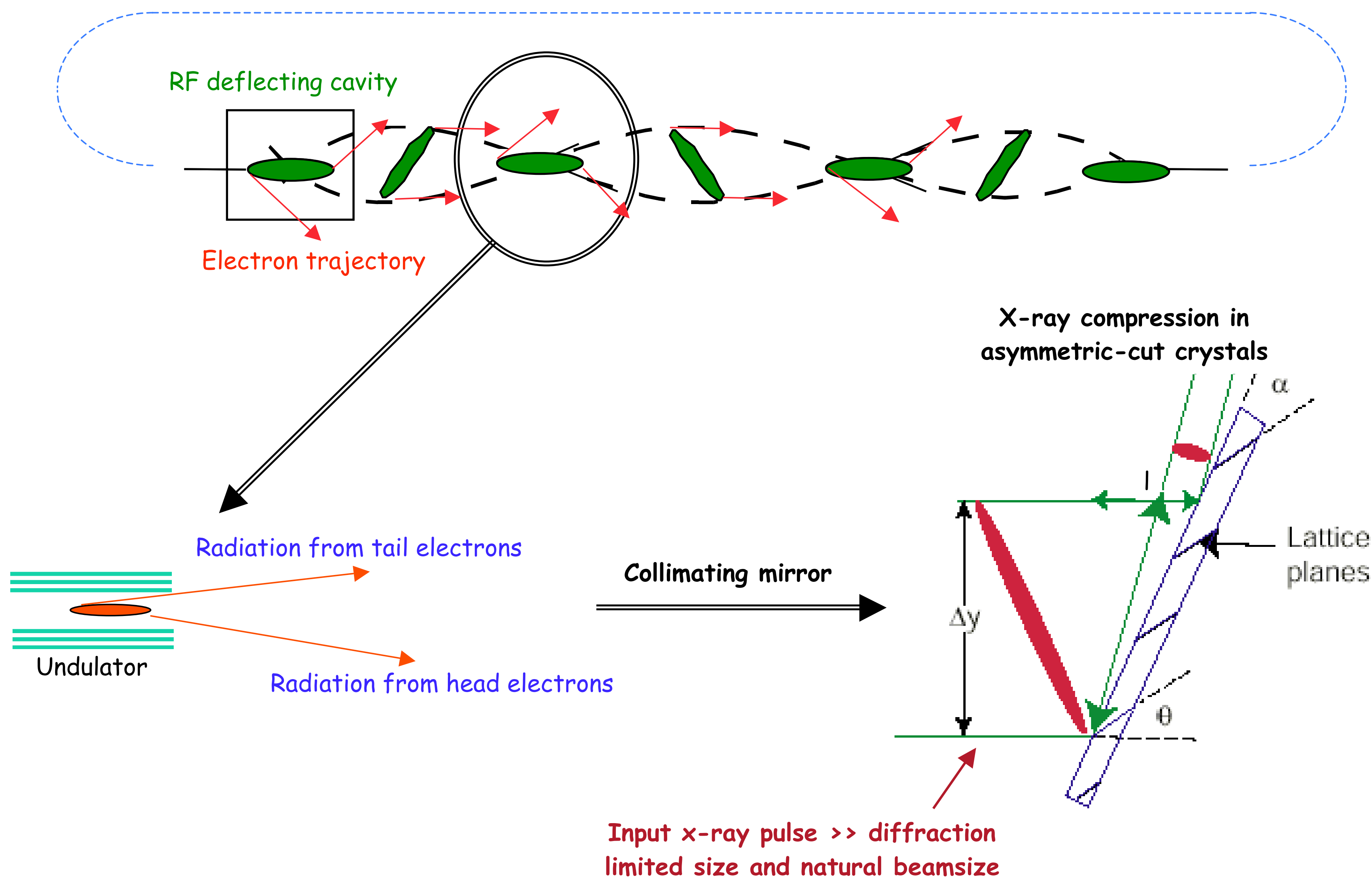
Short-pulse hard x-ray scheme conceived and developed at LBNL[1]



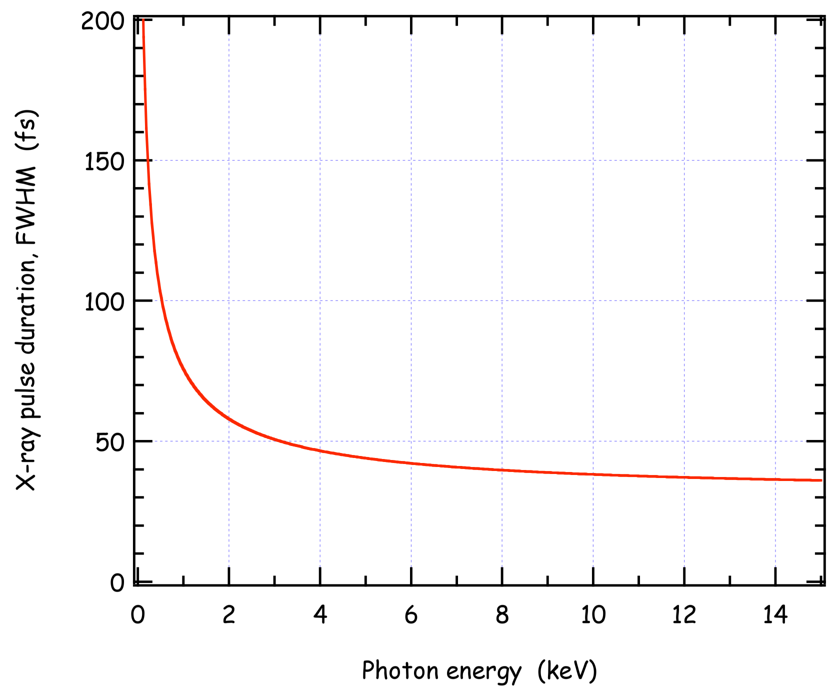
- Generate ~ nC high-brightness bunch in rf photocathode (3 mm-mrad @ 1 nC)
- Produce small vertical emittance from round beam (0.4 mm-mrad in vertical)
- Accelerate 2ps electron bunch to 3 GeV in recirculating linac
- Produce time / angle correlation within bunch
- Radiate in insertion devices1
- Compress x-ray pulse from 2 ps to ~ 50 fs in beamline optics

[1] A. Zholents et al "Generation of subpicosecond x-ray pulses using RF orbit deflection", NIM A 425 (1999) 385-389

Short-pulse hard x-ray scheme conceived and developed at LBNL

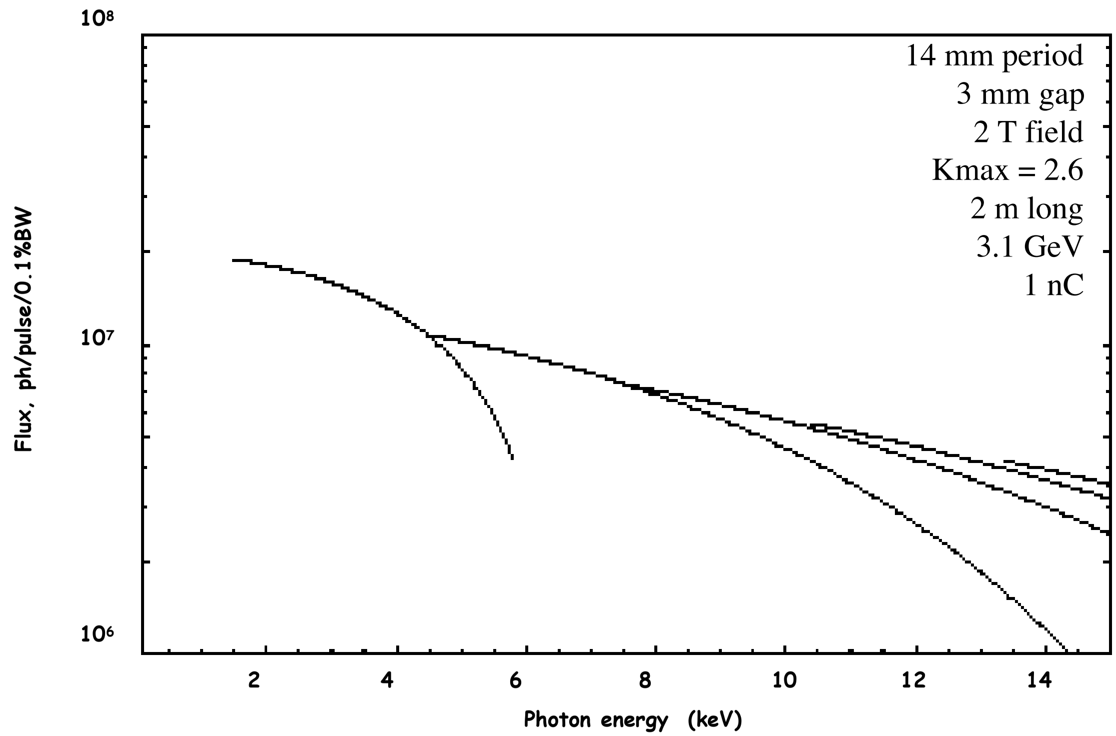


Hard x-ray pulse duration is determined by the accelerator parameters and radiation properties



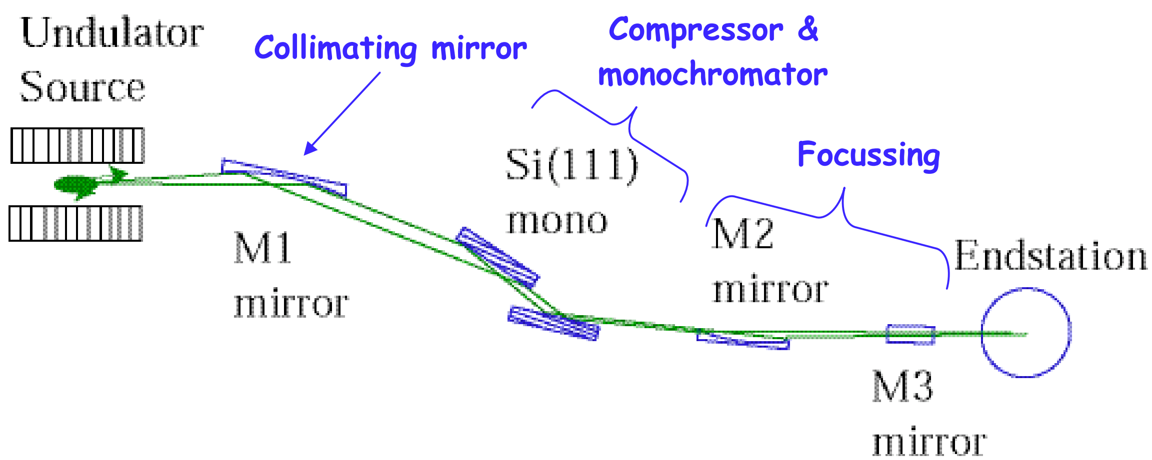
- The pulse duration is determined by
  - Beam emittance for shorter wavelengths
  - Optical diffraction for longer wavelengths
- The "flat beam" requirement (small electron beam emittance in one direction) defines pulse duration for hard x-rays
  - Small emittance in direction of head/tail kick
    - Flat-beam demonstrated at FNPL, LBNL is collaborator in this experiment

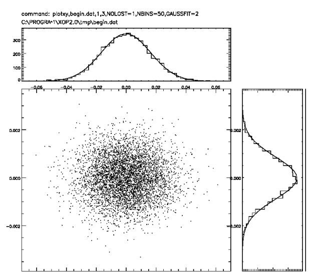
Hard x-ray flux from tunable superconducting undulator harmonics



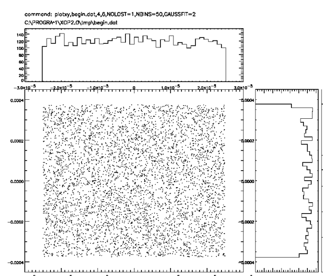
- Same flux/pulse as 3rd generation light sources
- 1000 times shorter pulse

Hard x-ray undulator beamline

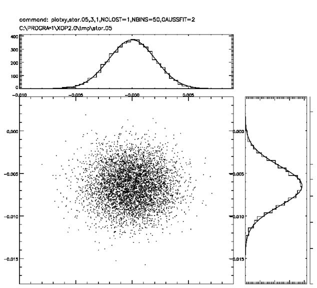




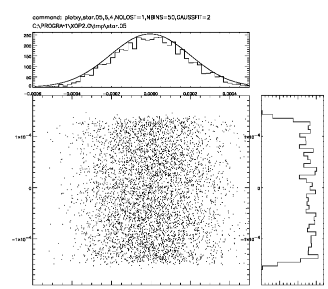
Source dimensions
390 μm (h) x 20 μm (v)



Source divergence
50 μrad (h) x 750 μrad (v)



Focus dimensions
48 μm (h) x 55 μm (v)



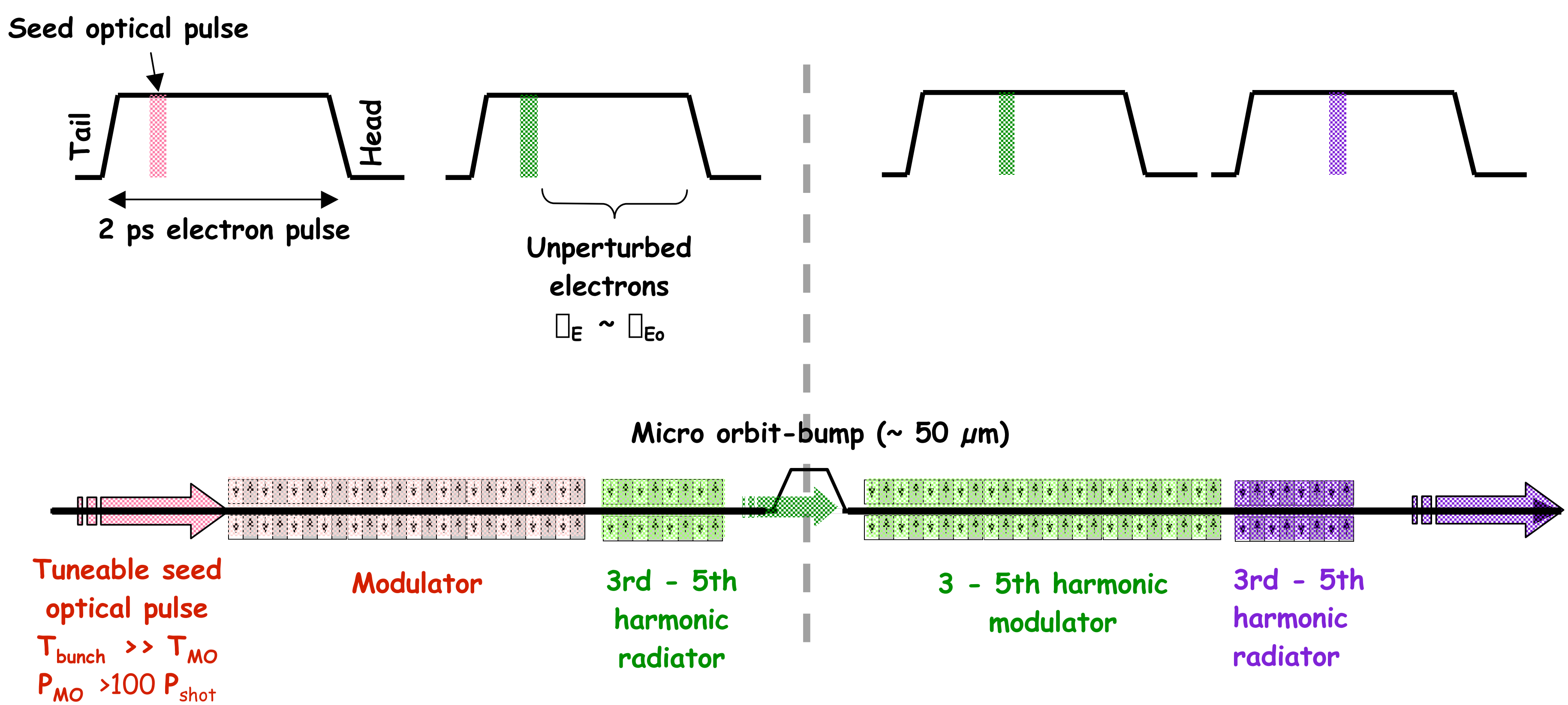
Focus divergence
500 μrad (h) x 300 μrad (v)

- Conventional optical elements
  - Temporal stability will be important

	Type	Coating and blank material	Dimensions (mm)	Radius (m)	Incidence angle(°)	Distance from source (m)
M1	Plane parabolic mirror	Pt-coated silicon	650 x 60	1430	89.6	5
X1, X2	Crystal	Silicon (111)	60 x 60		75.6912 [illegible] = -3.5	6
M2	Plane parabolic mirror	Pt-coated silicon	300 x 25	1430	89.6	7
M3	Plane elliptical mirror	Pt-coated silicon	200 x 20	339	89.6	10.667
Endstation						12

High Gain Harmonic Generation (HGHG) EUV and soft x-ray production

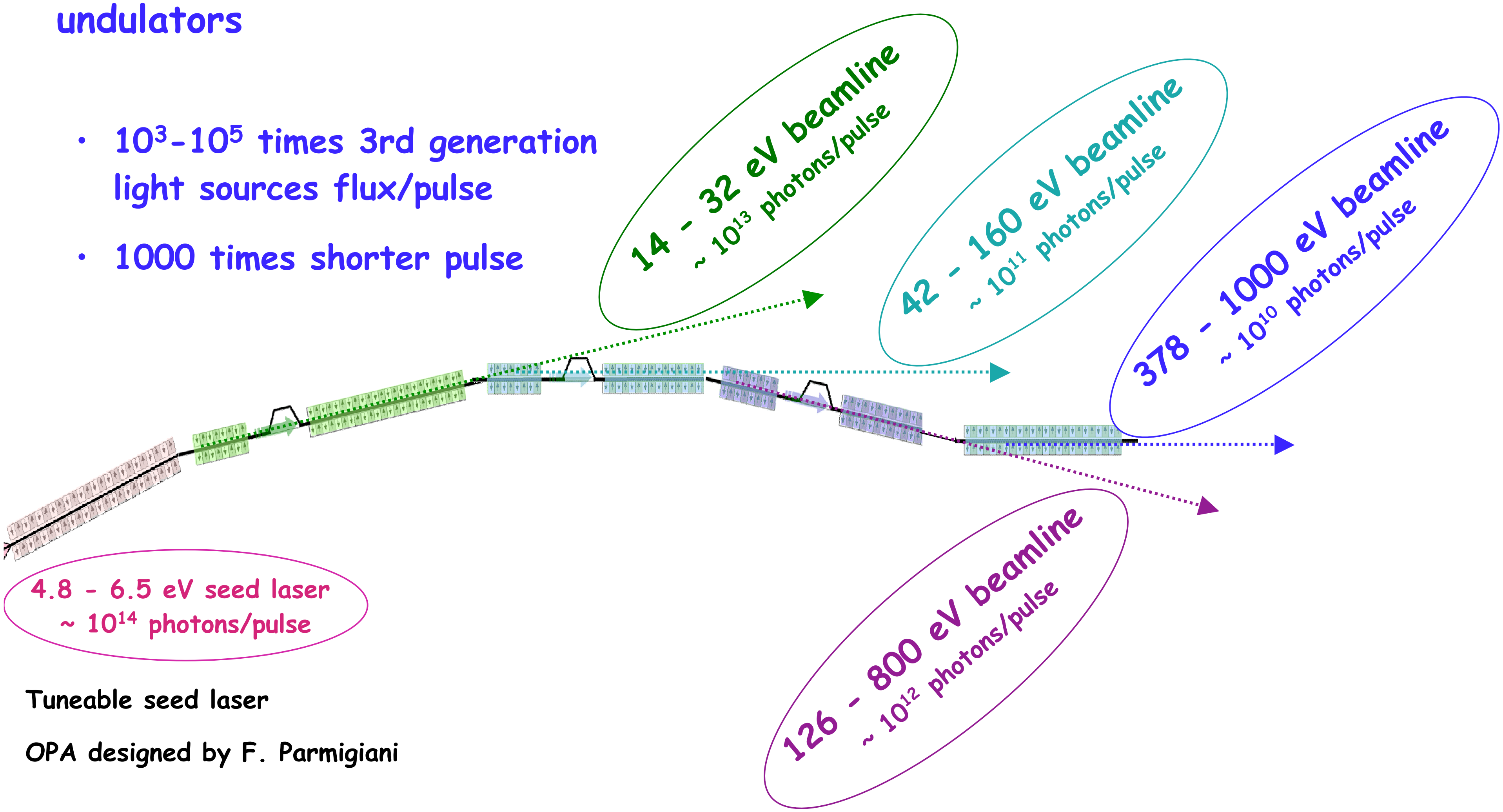
- *Seed optical pulse modulates a short section of the electron bunch*
- *Modulated section radiates coherently at a harmonic of the modulation wavelength*
  - Developed and demonstrated by L.-H. Yu et al, Brookhaven National Laboratory [1]



[1] L.-H. Yu et al, "High-Gain Harmonic-Generation Free-Electron Laser", Science **289** 932-934 (2000)

Multiple beamlines with 4-stage harmonic booster

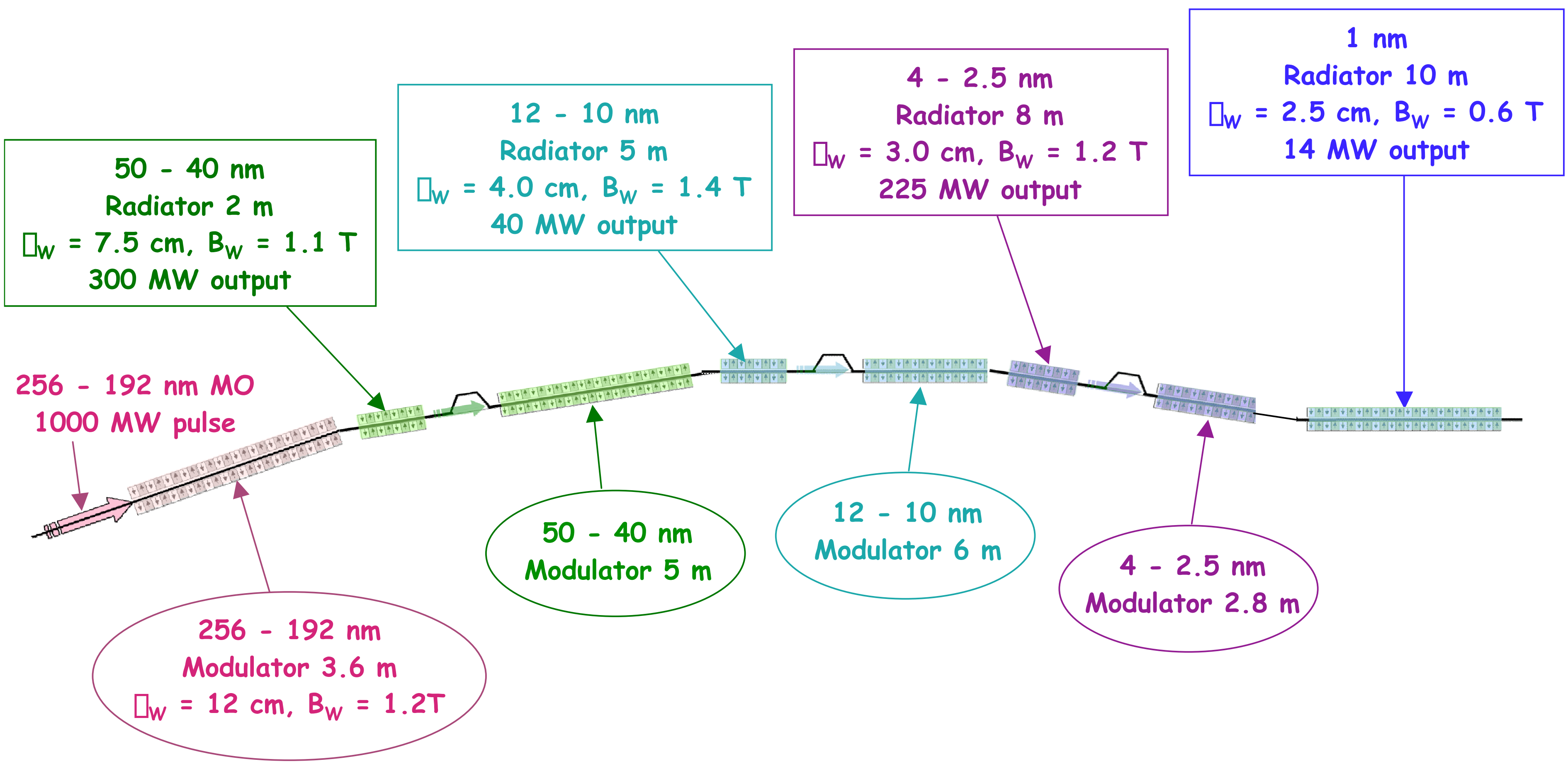
- Wide range of soft x-ray wavelengths accessible by tuning seed OPA and undulators
  - 10^3-10^5 times 3rd generation light sources flux/pulse
  - 1000 times shorter pulse



Tuneable seed laser

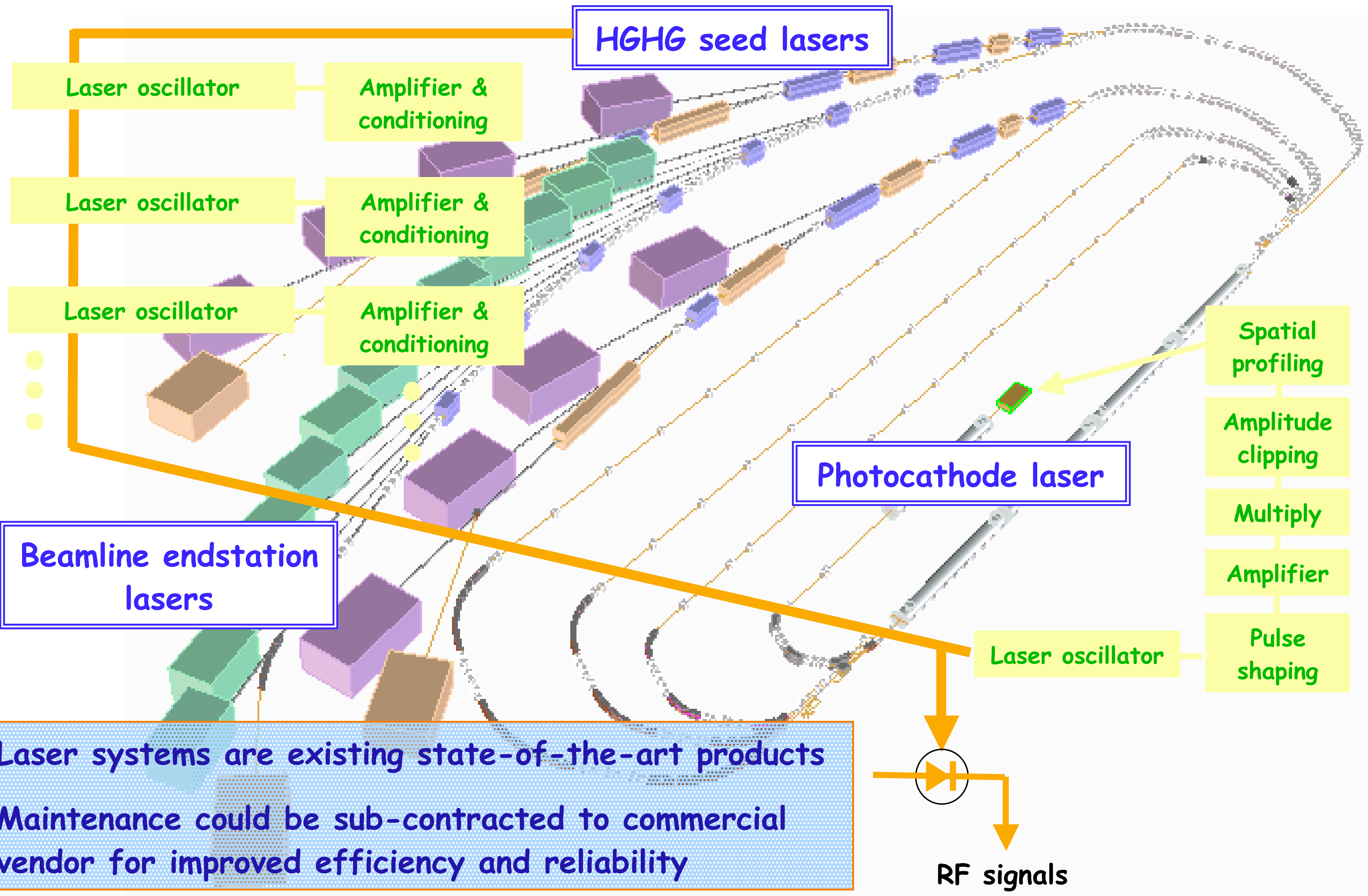
OPA designed by F. Parmigiani

Worked example 4-stage harmonic cascade



- Conventional undulator designs

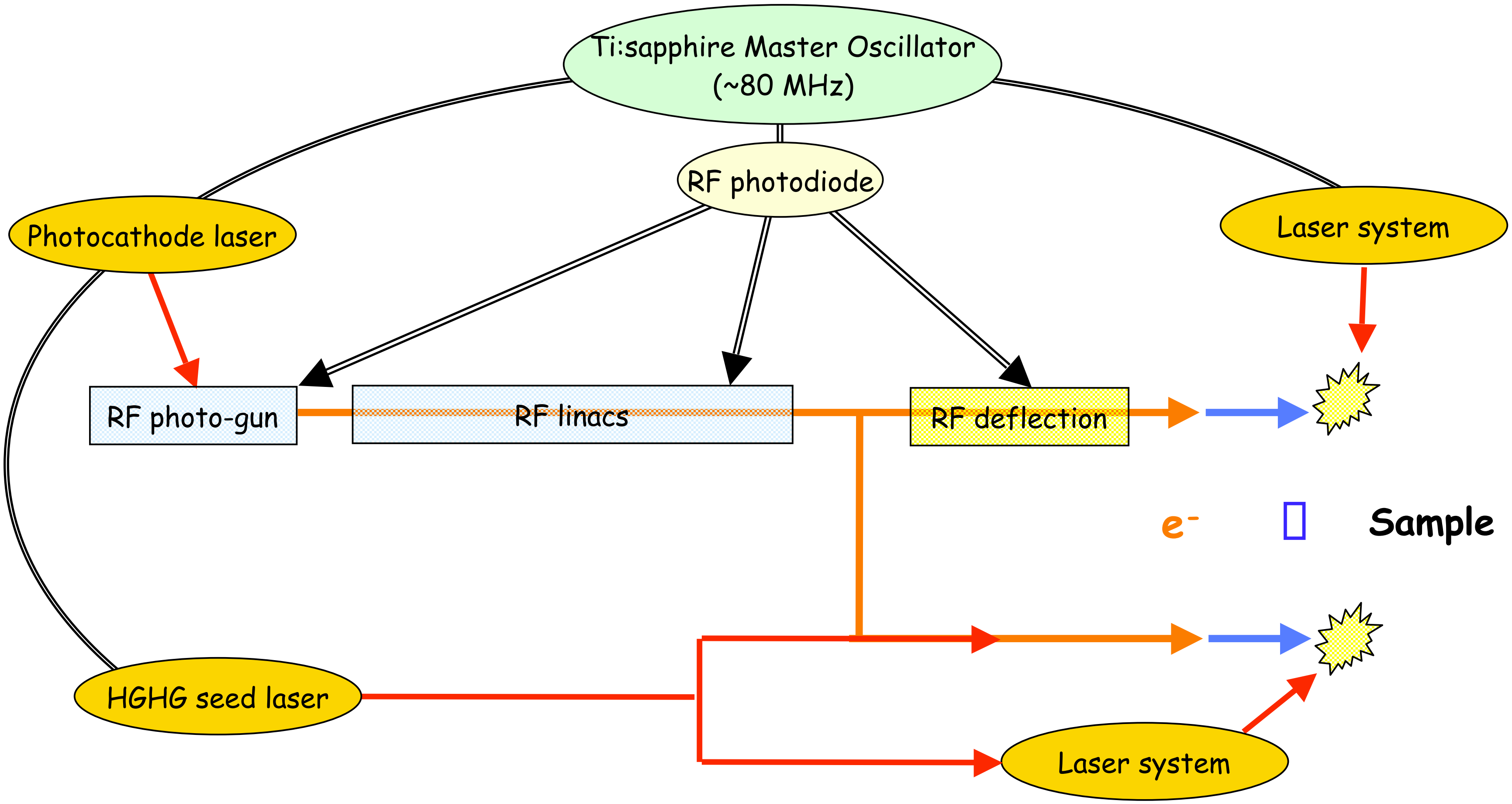
Sophisticated short-pulse laser systems are an integral component of the facility



Laser systems are existing state-of-the-art products

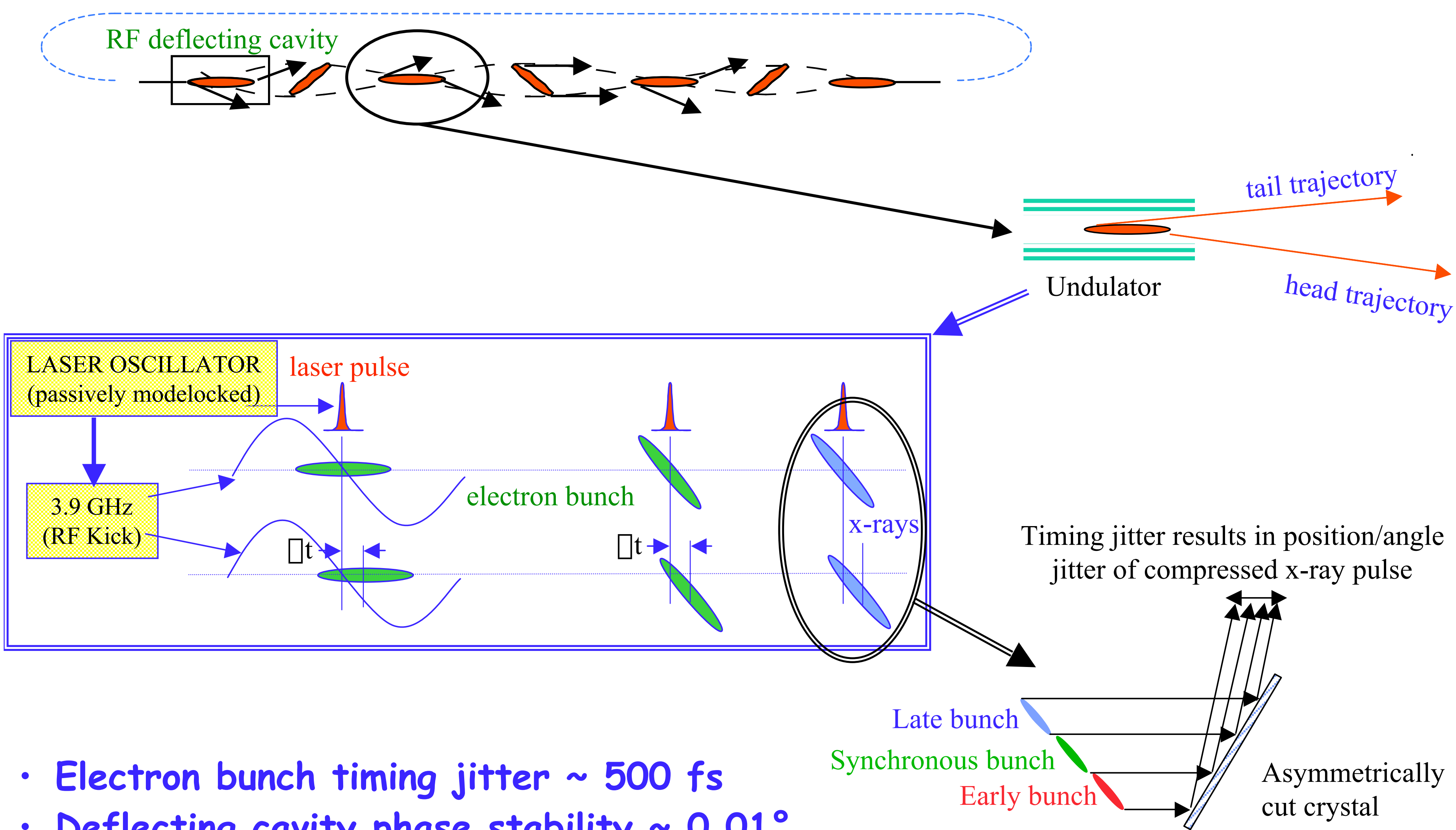
Maintenance could be sub-contracted to commercial vendor for improved efficiency and reliability

Synchronize systems to allow controlled delay between pump pulse and x-ray pulse



- "Fast" feedback on accelerator systems control pulse-pulse stability
- Measured timing error updates feedback systems to compensate "slow" drift

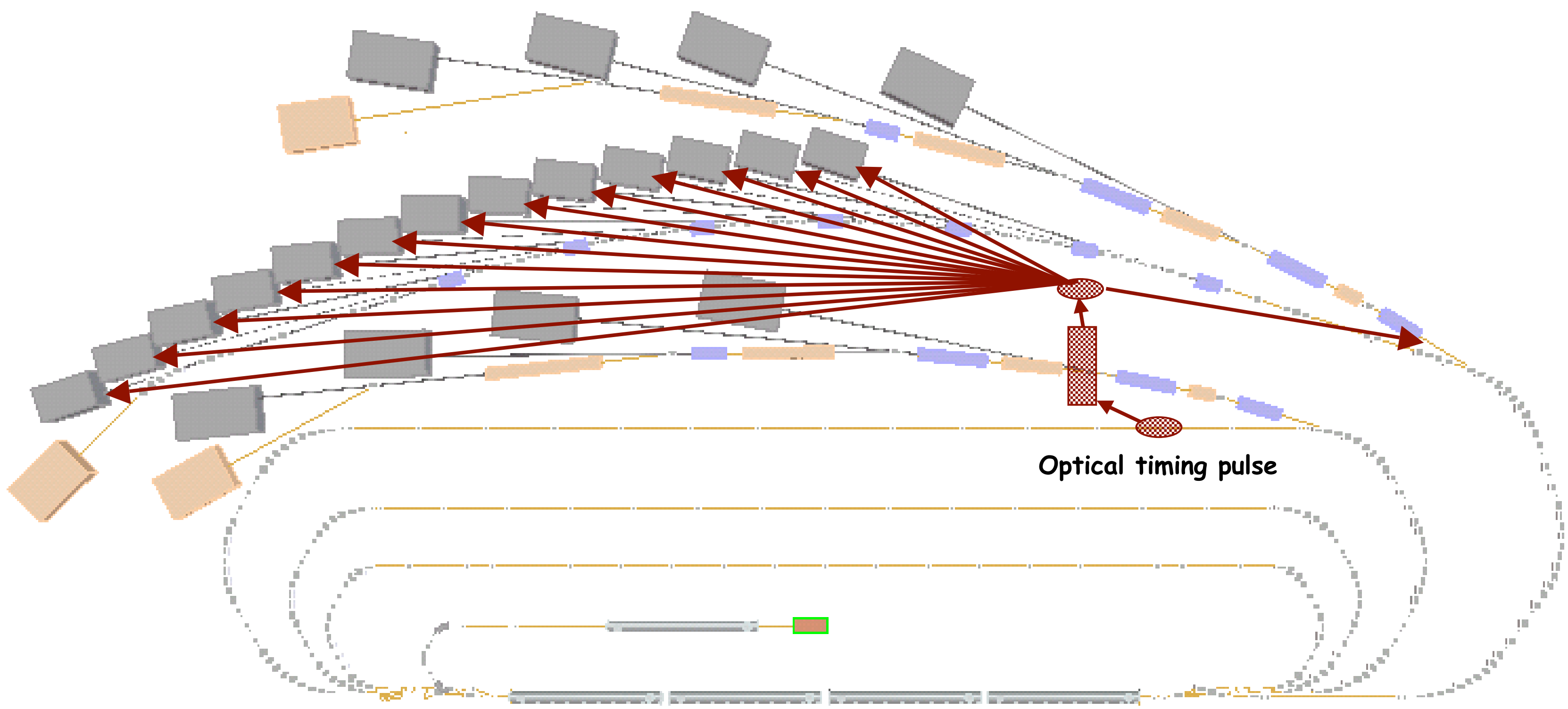
Synchronize deflecting cavities and pump laser for hard x-ray production



- Electron bunch timing jitter ~ 500 fs
- Deflecting cavity phase stability ~ 0.01°
  - 50 fs synchronization

John Corlett, February 2003

Ultimate synchronization from beam-derived optical pulses to seed end-station lasers



- ~ 1 μs turn-turn delay
  - Allows time for optical pulse manipulation, amplification, and distribution

Performance parameters

Synchronization

- Soft x-ray pulses locked to seed laser in HGHG process
  - Derive seed laser and sample excitation laser pulses from common oscillator
  - Independent of electron bunch timing
    - Goal 20 fs stability
- Hard x-ray pulses insensitive to electron bunch jitter
  - Phase stability of deflecting cavities via feedback
    - Goal 50 fs stability
- Beam-derived optical pulses for ultimate timing stability

Pulse duration

  - $\leq$ 50 fs hard x-rays
    - Bunch emittance, diffraction limit, deflecting voltage
  - EUV and soft x-ray adjustable 50-200 fs initially, goal 20 fs or less
    - Seed laser, slippage in FEL process

Contd.

Contd.

Performance parameters

Wavelength tuning

- EUV and soft x-ray
  - Adjust seed laser, HGHG undulator gaps
  - Adjust monochromator
- Hard x-ray
  - Adjust superconducting undulator current
  - Adjust monochromator

Polarization

- EUV and soft x-ray
  - Circular polarization from helical undulators
    - Switchable LH, RH
- Hard x-ray
  - Linearly polarized

Contd.

Contd.

Performance parameters

Pulse energy

- Goal 10^7 photons/pulse hard x-rays
    - Bunch charge, undulator length
- 10^8 - 10^{13} photons/pulse EUV / soft x-rays
    - Bunch charge, seed laser, FEL gain

Flux stability

- High rep-rate results in rapid averaging
    - < 10 % shot-shot variation hard x-ray
    - 10-20 % shot-shot variation soft x-ray
    - ~ 0.1% in few seconds at 10 kHz rep. rate

Repetition rate

- Up to 10 kHz for nominal pulse energy
- Higher rates for reduced flux/pulse
    - Energy recovery for higher beam power

Contd.

Contd.

Performance parameters

Coherence

- EUV / soft x-rays spatially and temporally coherent

Power density

- 10^{13} W/cm^2 EUV and soft x-ray readily achievable
  - Seed pulse, bunch charge density

Energy chirp

- Energy chirp of approximately 1% possible for dedicated operating mode
  - Pass through linac off-crest

Machine feasibility

- Two year study documented in LBNL publication LBNL-51766
  - Physics design optimizied for ultrafast x-ray production with conservative accelerator physics approach
    - 2 ps bunch length, low average current
      - Generate 10's fs x-rays from ps bunches, avoids multi-bunch problems, only 30 kW nominal beam power in final arc
    - Recirculating linac configuration is refined, flexible, and upgradeable
  - Physics parameters demonstrated or modest extrapolation
  - Engineering refinements will be needed in some technologies to improve reliability and reduce costs

- Design builds on LBNL expertise and experience in accelerator physics, engineering, and related technologies
  - Center for Beam Physics / Accelerator and Fusion Research Division / Advanced Light Source Division
    - ALS, B-factory, LHC, SNS, NLC, Thomson scattering, ALS slicing source

Machine feasibility study

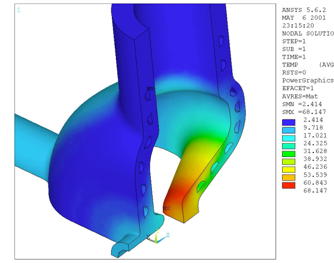
- Accelerator physics design has addressed detailed questions
  - Space charge, energy spread, bunch compression, coherent synchrotron radiation, cavity wakefields, resistive wall impedance, magnet errors, magnet misalignment, instrumentation, rf cavity design, flat-beam production, x-ray beamline design, laser systems, synchronization

- Engineering effort has developed conceptual designs in key areas, and confidence in cost estimates
  - High rep-rate rf photocathode gun, magnet systems, vacuum systems, beam dump, linac cryomodule design, cryogenics systems, rf power systems, conventional facilities

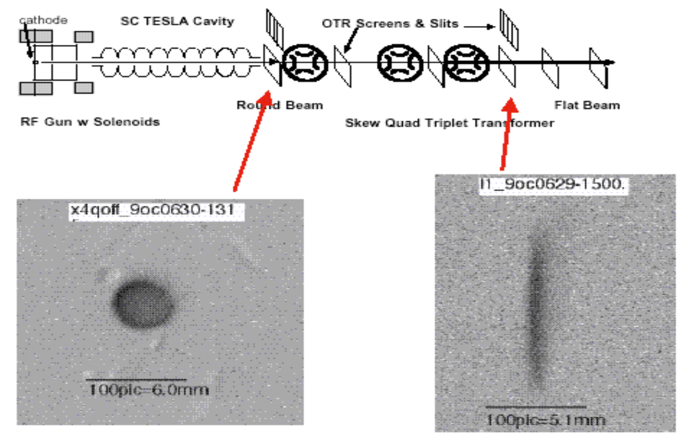
No show-stoppers

Technologies for LUX exist, proposed engineering developments will meet requirements

- High-brightness high-rep-rate photocathode gun
  - Required 3 mm-mrad @ 1 nC demonstrated [1], we have developed high-power design
- Flat-beam production
  - <1 mm-mrad demonstrated [2], we are collaborators in this experiment
- CW superconducting RF
  - We have developed engineering modifications for the TESLA design, TJNAF upgrade may use 20 MV/m [3]
- Lasers and optical distribution
  - We are developing laser expertise at existing ultrafast experiments (ALS, L'Oasis)
- Superconducting narrow-gap undulators
  - We are developing designs and harmonic correction schemes, Karlsruhe & ACCEL work [4]

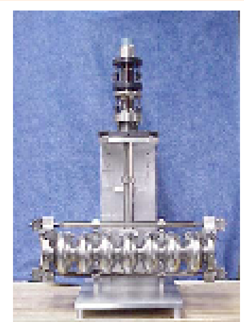


High-brightness 10 kHz RF photocathode gun



Round beam image on fluorescent screen

Flat beam image on fluorescent screen



J-Lab upgrade cavity

[1] J.-P. Carneiro, H. T. Edwards, M. J. Fitch, W. H. Hartung, "Emittance Measurementgs at the A0 Photo-Injector", Proc. XXth International Linac Conference, Monterey, 2000

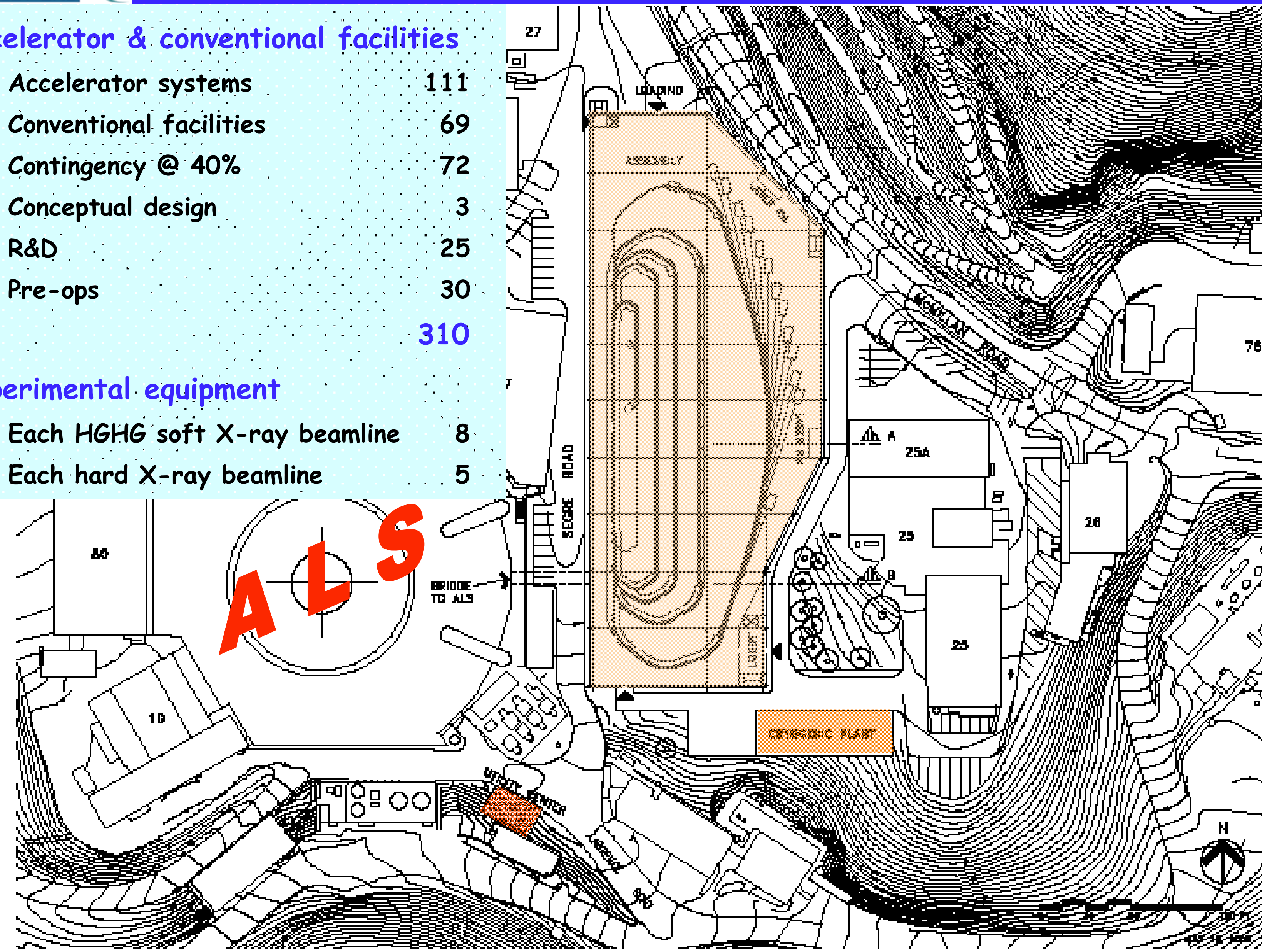
[2] D. Edwards, et al, "The Flat Beam Experiment at the FNAL Photoinjector", Proc. XXth International Linac Conference, Monterey, 2000

[3] L. Harwood, C. Reece, "CEBAF at 12 and 25 GeV", Proc. SRF2001, Tsukuba, Japan, Sept. 2001

[4] A. Geisler et al, "A Superconducting Short Period Undulator", Proc. PAC2001, Chicago, June 2001

Several potential sites identified "Old Town" site maximizes synergies with ALS

- Accelerator & conventional facilities
  - Accelerator systems 111
  - Conventional facilities 69
  - Contingency @ 40% 72
  - Conceptual design 3
  - R&D 25
  - Pre-ops 30
- 310
- Experimental equipment
  - Each HGHG soft X-ray beamline 8
  - Each hard X-ray beamline 5



LUX - conclusions

- **LUX presents an opportunity for an outstanding dedicated ultrafast x-ray science facility**
  - Extremely versatile experimental capabilities
  - Multiple beamlines for many user groups
  - Feasible machine design using a refined, flexible, upgradeable, concept
  - Technologies demonstrated, engineering refinements needed
  - Excellent science opportunities across all fields

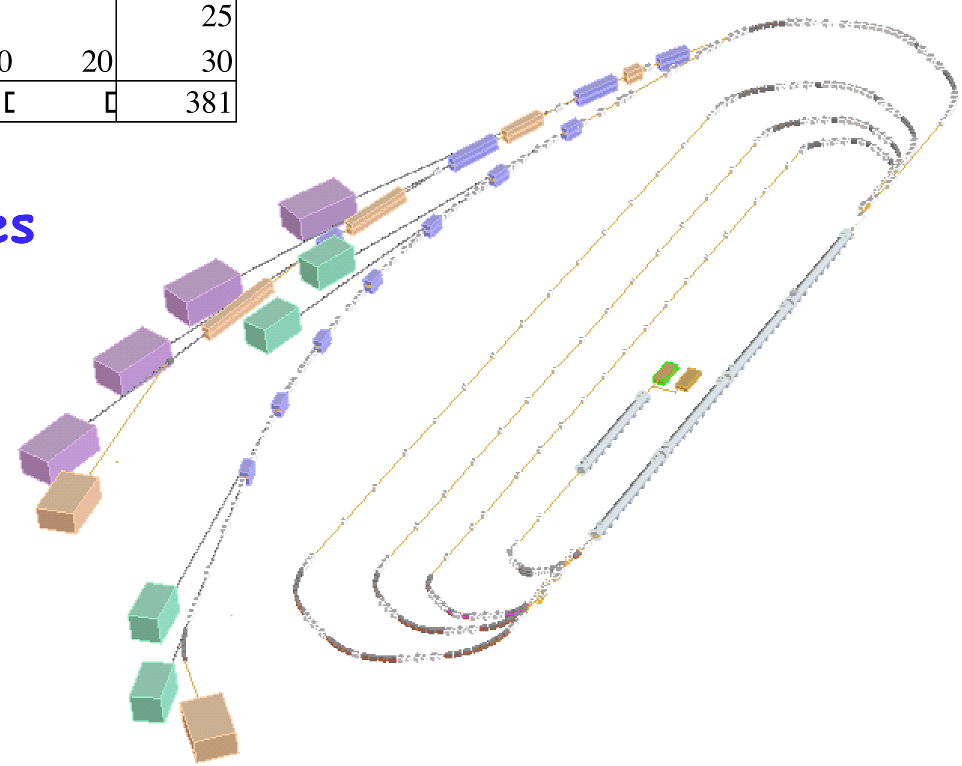
We are ready to present mission need statement and start conceptual design

Schedule of project funding

	Dollars in millions FY'03						
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Total
Facility cost:							
PED		15	15				30
Construction			30	100	60	10	200
Contingency							93
Other project costs							
Conceptual design	3						3
R&D	10	10	5				25
Pre-ops					10	20	30
Total							381

Initial complement of eight beamlines

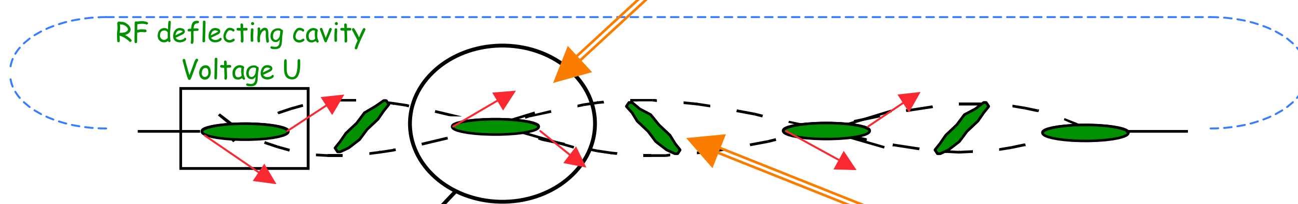
Capacity for ~ 20 beamlines



Femtosecond x-ray pulses from picosecond bunches
Reduces problems associated with ultra-short electron bunches

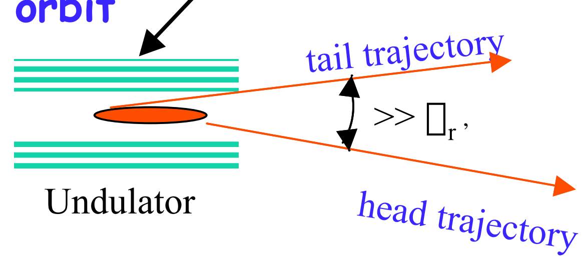
- Deflecting cavity introduces angle-time correlation into the ~ ps electron bunch

$$\Delta y'(z) = \frac{eU}{E_{beam}}\sqrt{\frac{\beta_{cavity}}{\beta_{ID}}}\,\sin(k_{rf}z)$$



$$\Delta y(z) = \frac{eU}{E_{beam}}\sqrt{\beta_{cavity}\,\beta_{bend}}\,\sin(k_{rf}z)$$

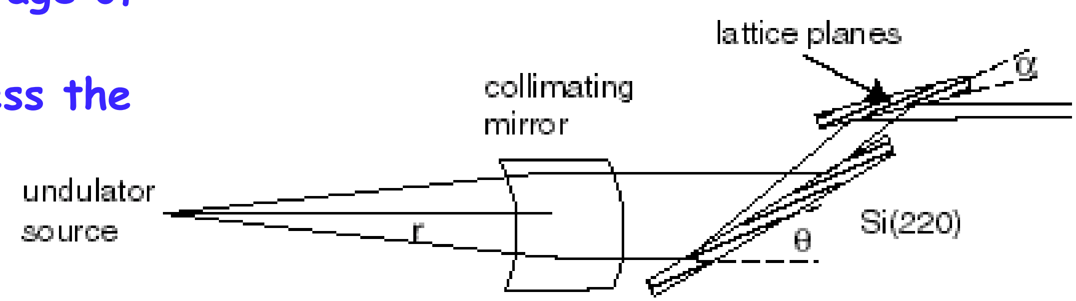
- Electrons oscillate along the orbit



Bunch tilt ~ 140 μ-rad (rms)

Radiation opening angle ~ 7 μ-rad @ 1Å

- Crystal x-ray optics take advantage of the position-time correlation, or angle-time correlation to compress the pulse



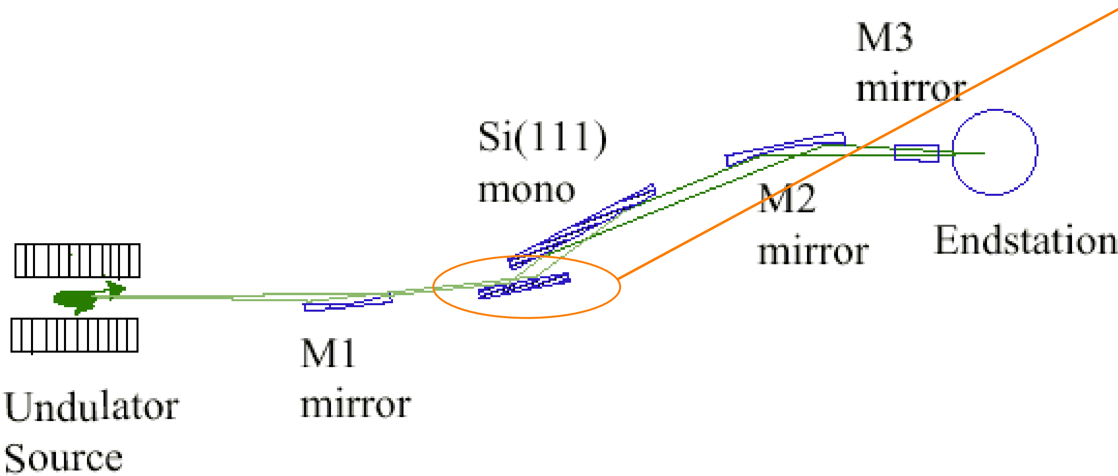
X-ray pulse compression

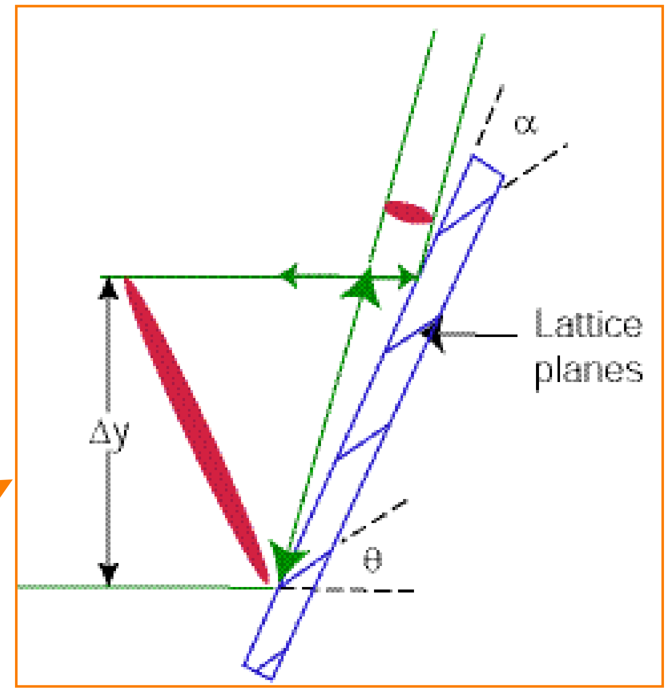
- Optical path length Δl varies linearly with position Δy on crystal

- We propose to use a pair of asymmetrically cut silicon crystals following collection optics

$$\Delta l = 2\,\Delta y \frac{\sin\alpha\ \sin\theta}{\sin(\theta+\alpha)}$$

Crystals	λ	Δy	θ	α	Δl
Si(111)	1.5 A	3.8 mm	14.309°	-3.5°	0.6 mm (2 ps)



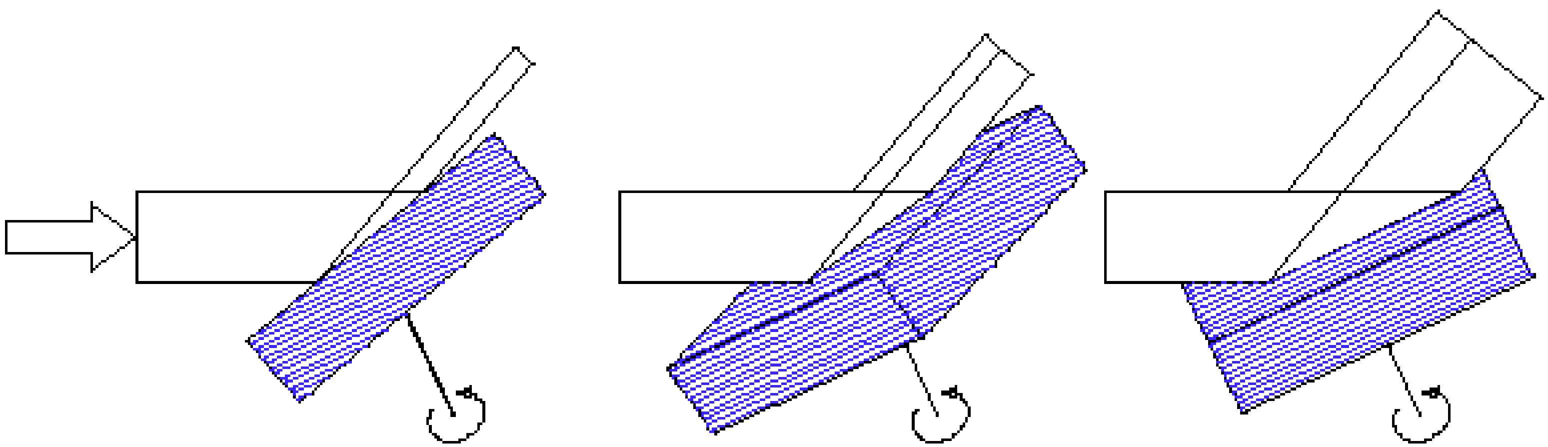


John Corlett, February 2003

Tuning x-ray pulse compression as a function of photon energy

- Add rotation about axis normal to Bragg planes □ to rotation of Bragg angle □

□ Variation of crystal asymmetry a keeping pulse compression fixed



□ = 0°
□ = 15°

□ = 45°
□ = 11°

□ = 90°
□ = 0°

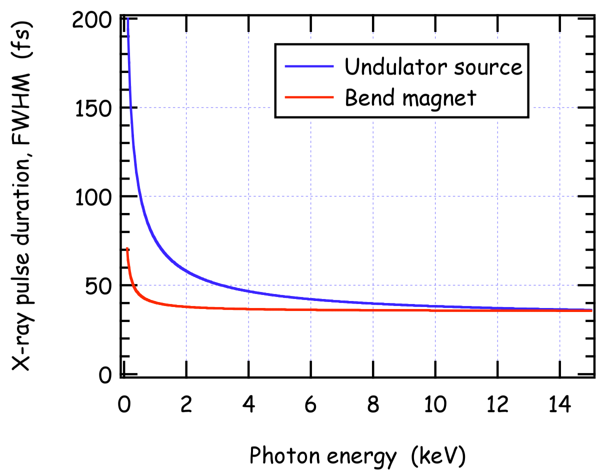
X-ray pulse duration

Bend magnet x-ray pulse duration

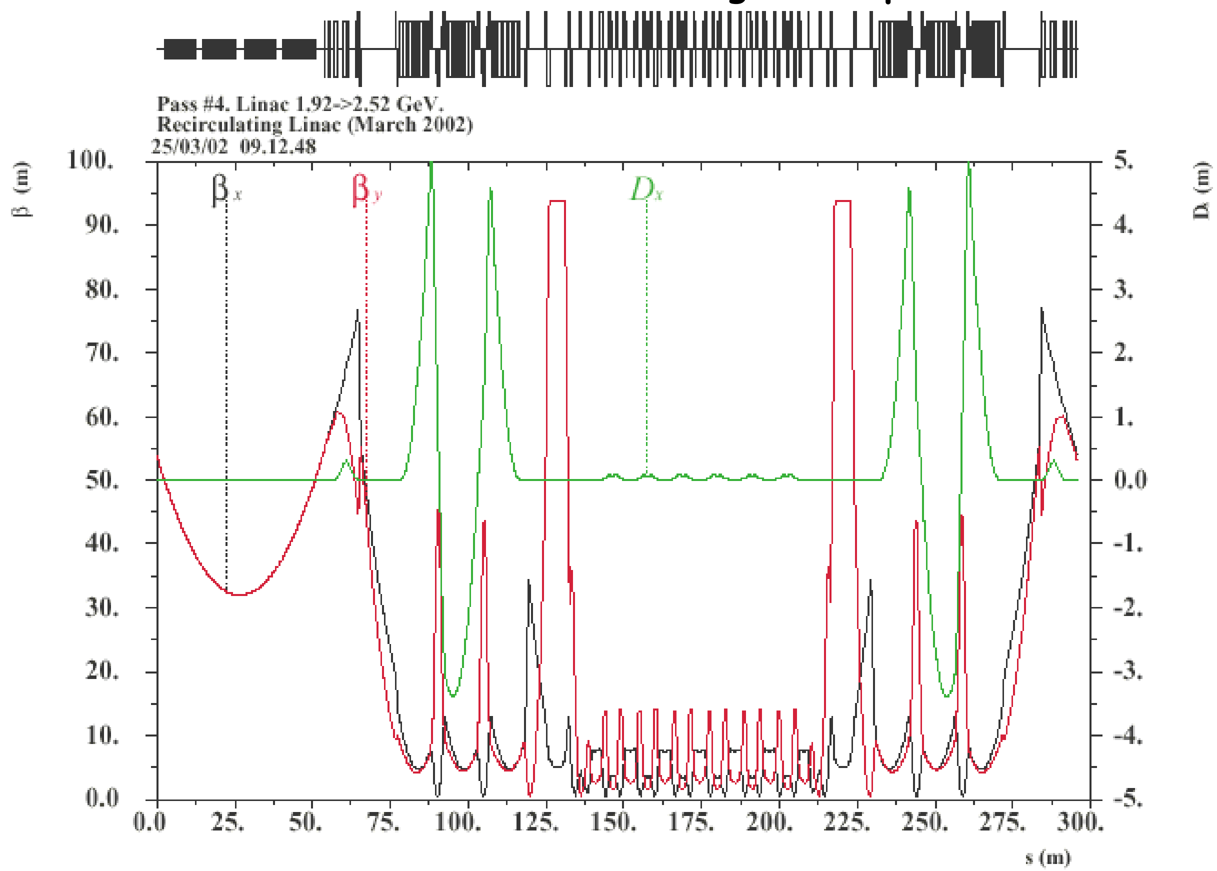
$$\square_{x-ray} \geq \frac{E_{beam}}{k_{rf}\, e\, U}\, \square^{rf}_{y'} \sqrt{1 + \left(\frac{\square_r}{\square_y}\right)^2}$$

Undulator x-ray pulse duration

$$\square_{x-ray} \geq \frac{E_{beam}}{k_{rf}\, e\, U}\, \square^{rf}_{y'} \sqrt{1 + \left(\frac{\square_{r'}}{\square_{y'}}\right)^2}$$

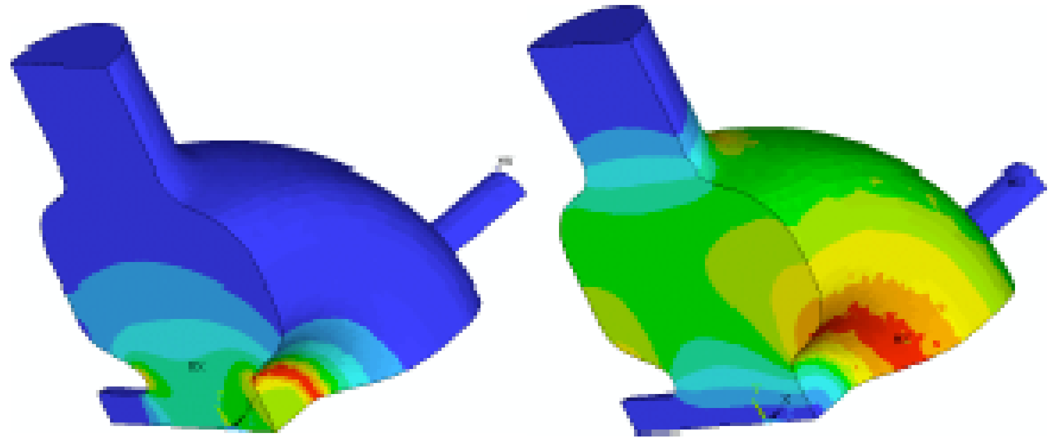


Lattice functions through final pass

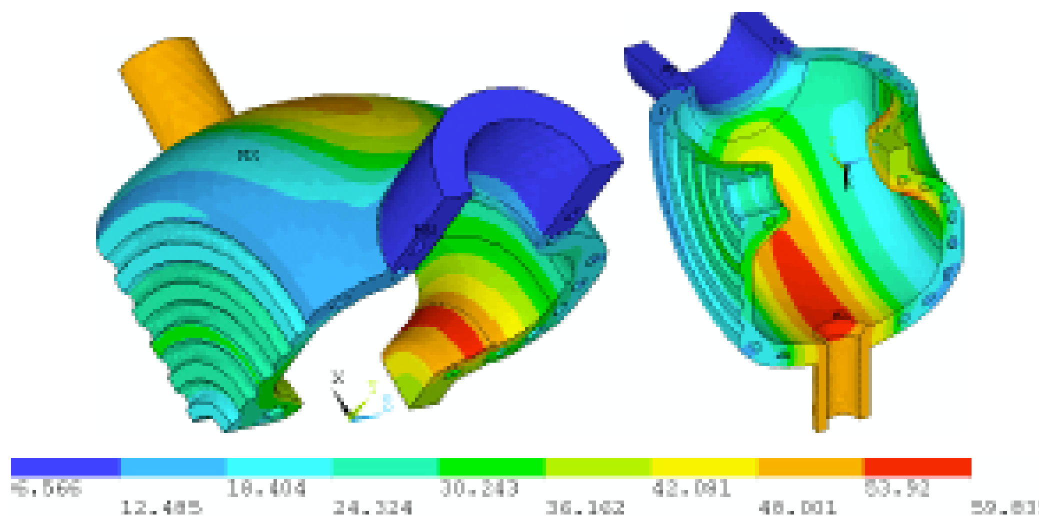


RF gun development
ANSYS model

	Gun cell	Cell 2 & 3
Frequency	1.3 GHz	1.3 GHz
Rep. rate	10 kHz	10 kHz
Duty factor	~5%	~5%
E_o	64 MV/m	43 MV/m
P_{peak}	581 kW	1550 kW
$P_{average}$	29 kW	77.5 kW
$P_{dens\ max}$	110 W/cm^2	107 W/cm^2

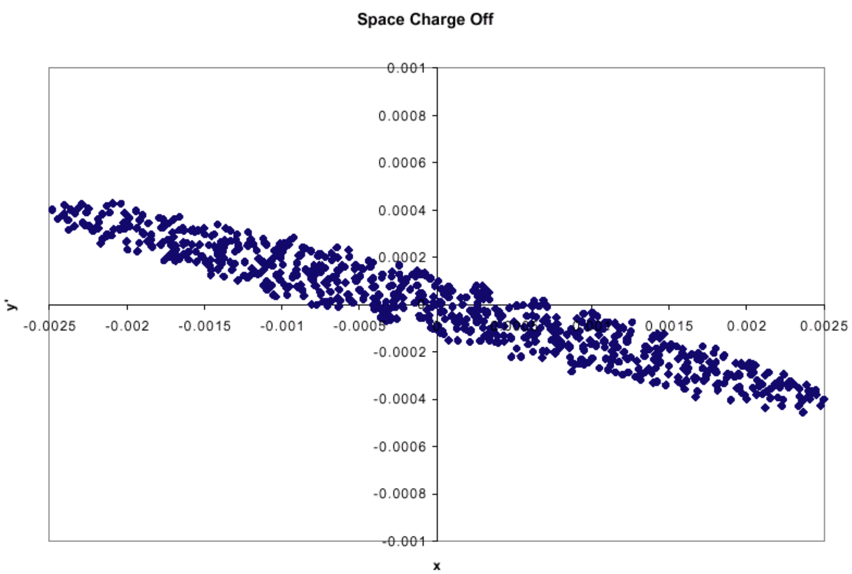


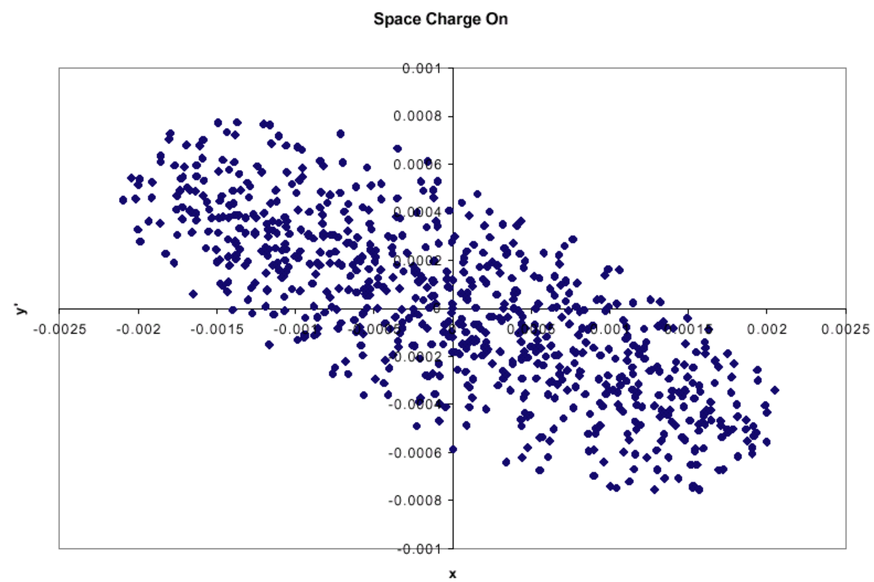
Surface electric and magnetic fields



Temperature above cooling water

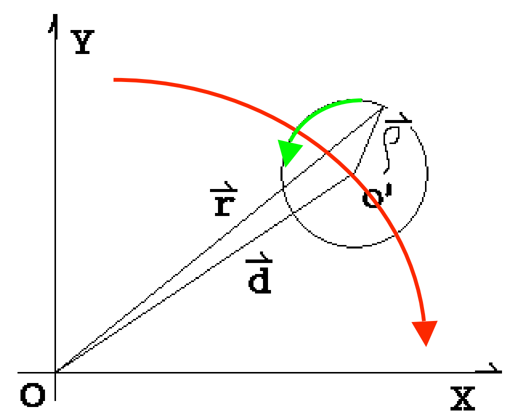
Flat beam modeling with PARMELA, MAFIA, HOMDYN, ASTRA





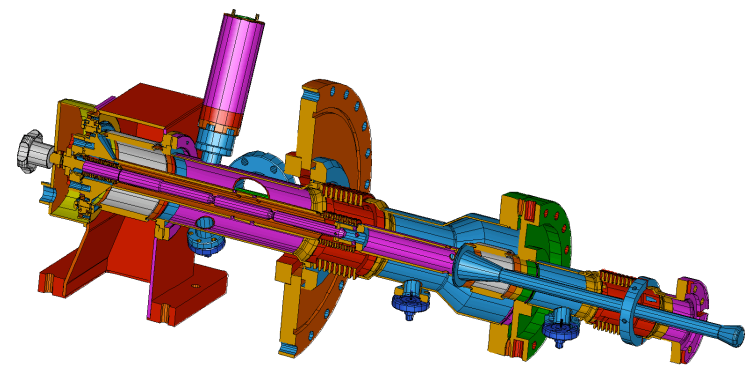
- Analytical model
  - Characterize circular beam in circular modes
    - Uncorrelated (anti-clockwise) mode
    - Correlated (clockwise) mode
  - Transform to x – y modes

1.0 nC	ε_+ = 47.1 um, ε_- =0.70 um
	ε_x = 47.1 um, ε_y = 0.72 um
0.1 nC	ε_+ = 45.5 um, ε_- = 0.013 um
	ε_x = 45.5 um, ε_y = 0.019 um

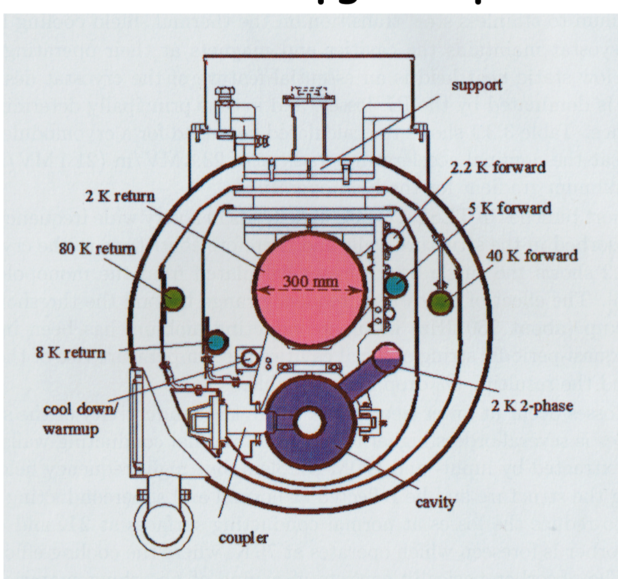


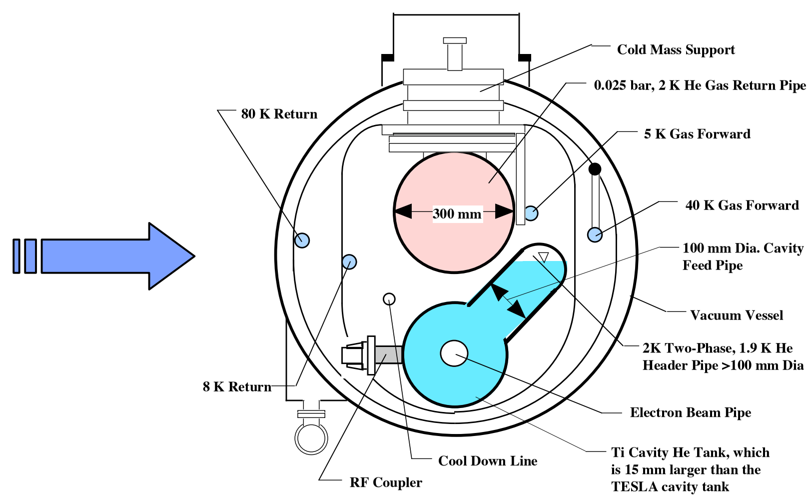
CW superconducting RF

- 1.3 and 3.9 GHz systems
  - Accelerating structures
  - Linearizing cavity
  - Deflecting cavities



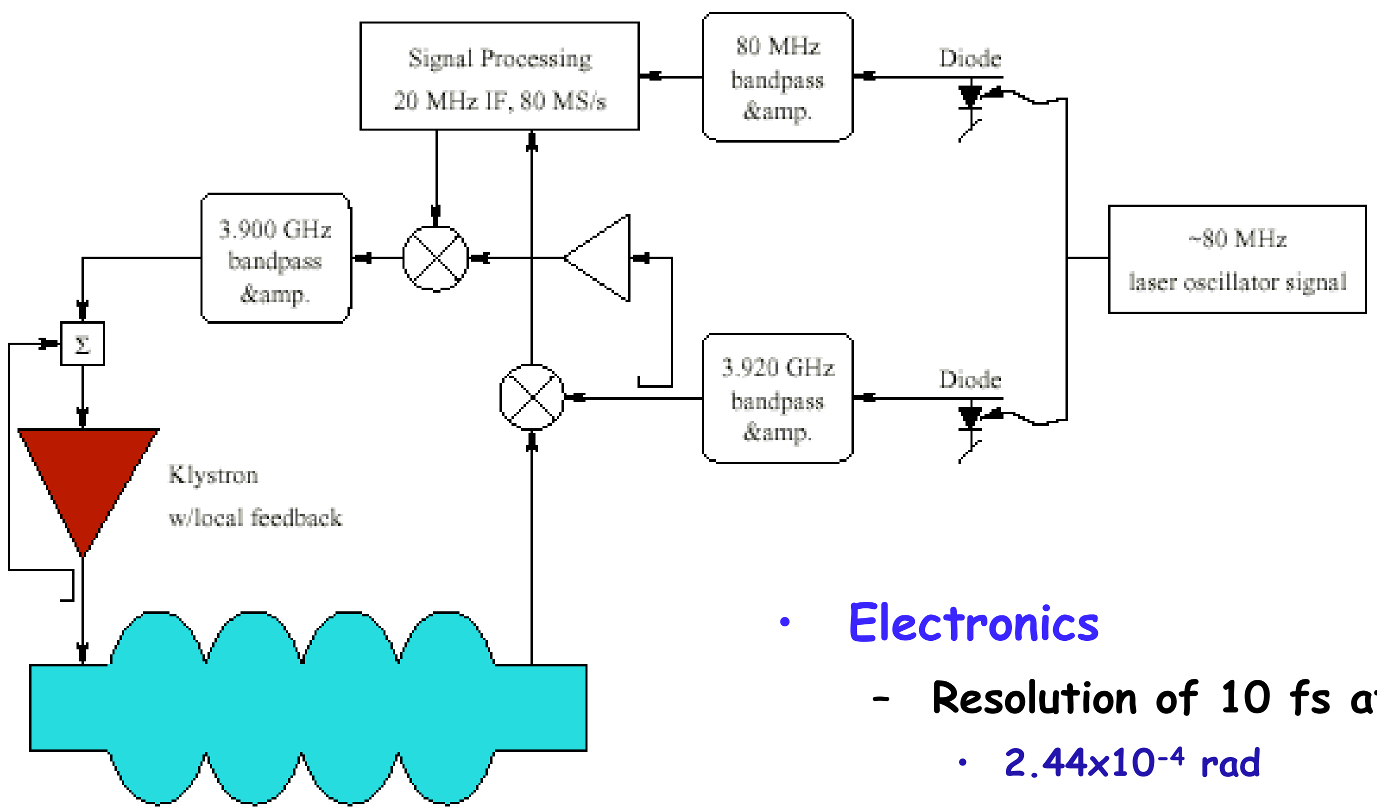
- Cavity thermal management
  - Conduction through He bath increased
    - J-Lab upgrade plan to develop 20 MV/m





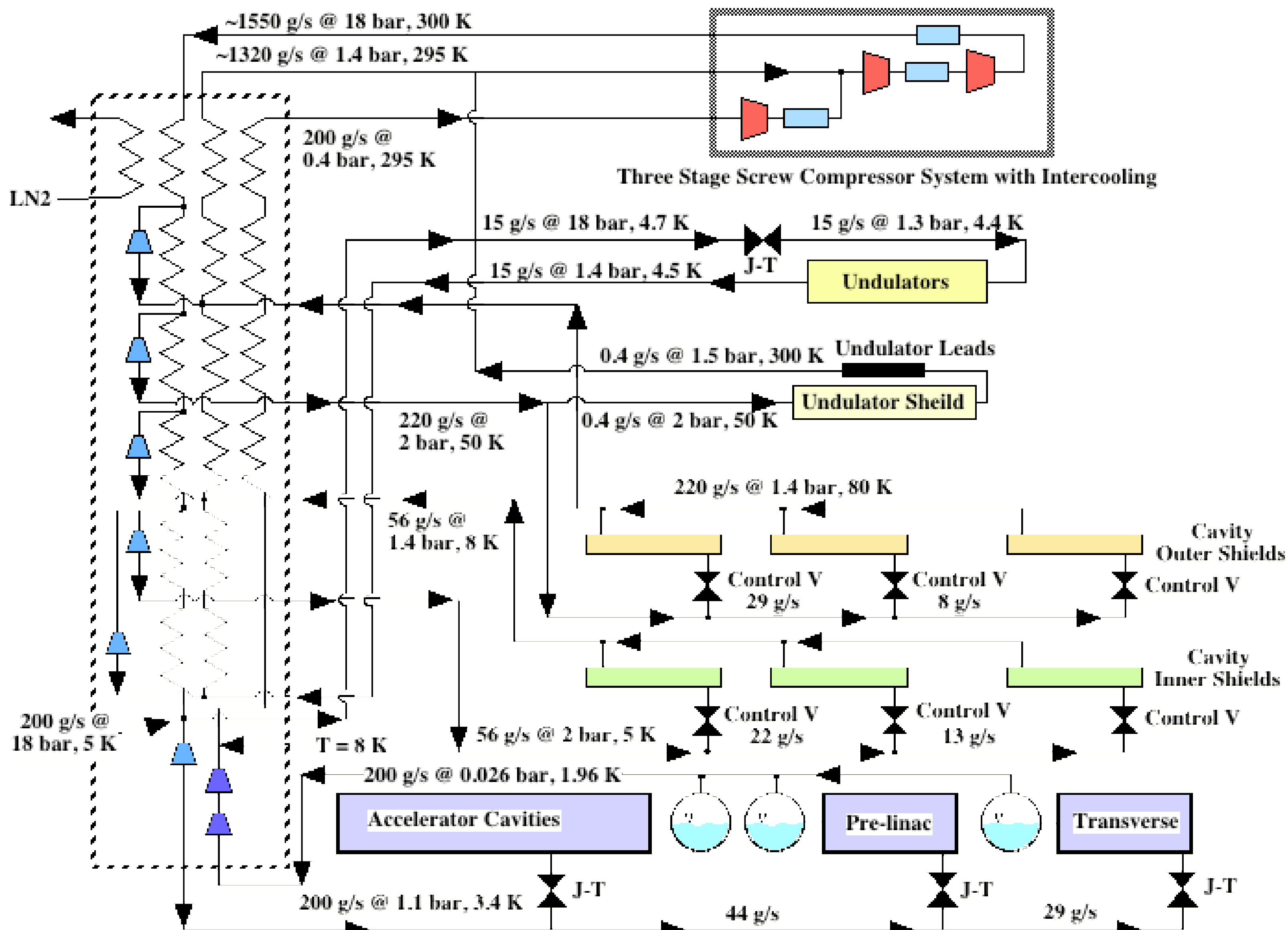
Deflecting cavity RF control

- Control cavity phase and amplitude to minimize timing jitter
  - "Fast" feedback
  - Update setpoint from measured timing drift



- Electronics
  - Resolution of 10 fs at 3.9 GHz
    - 2.44×10^{-4} rad
  - 14-bit ADC at 80 MHz

Cryogenics systems



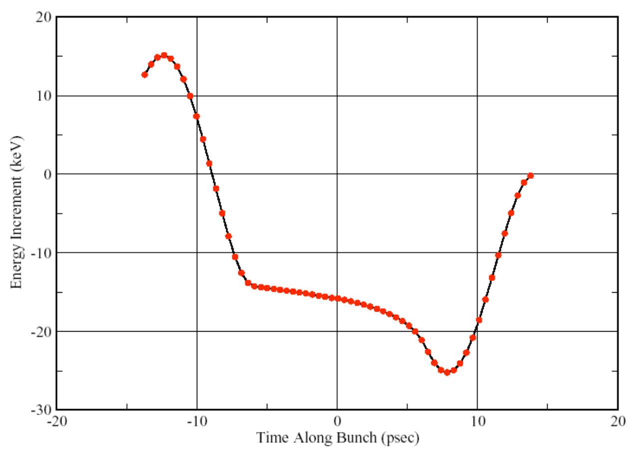
Delay lines and path lengths

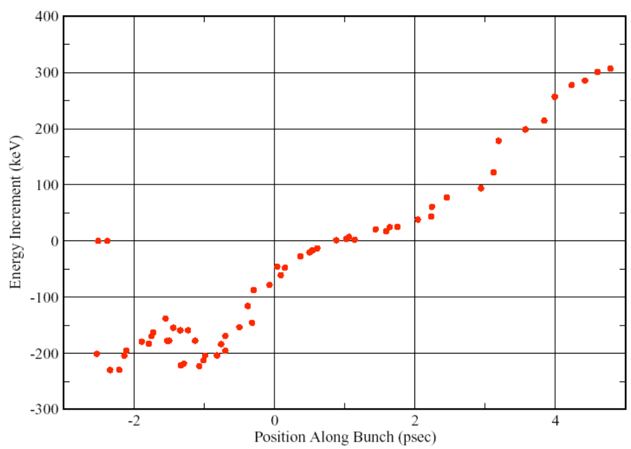
- Need flexible delay to match the path length of the laser pulse and the x-ray pulse at each beamline endstation
- Optical delay kept to minimum to preserve stability
- Master oscillator is extremely stable delay
  - Beamline users can select any pulse from the 81.25 MHz train of pulses
  - 12.3 ns pulse separation

- Stability over time period of the required delay
  - ~ 10 μs
  - 10 μs corresponds to ~ 812 round-trips in the master oscillator
  - For timing accuracy of 30 fs, the path length variation in this time must not exceed 10 μm
    - 0.012 μm per round-trip
  - 12 nm in 12.3 ns
    - $\approx$ 1 ms^{-1}
  - Requires force beyond that generated from acoustic disturbances or piezoelectric transducer

Coherent synchrotron radiation

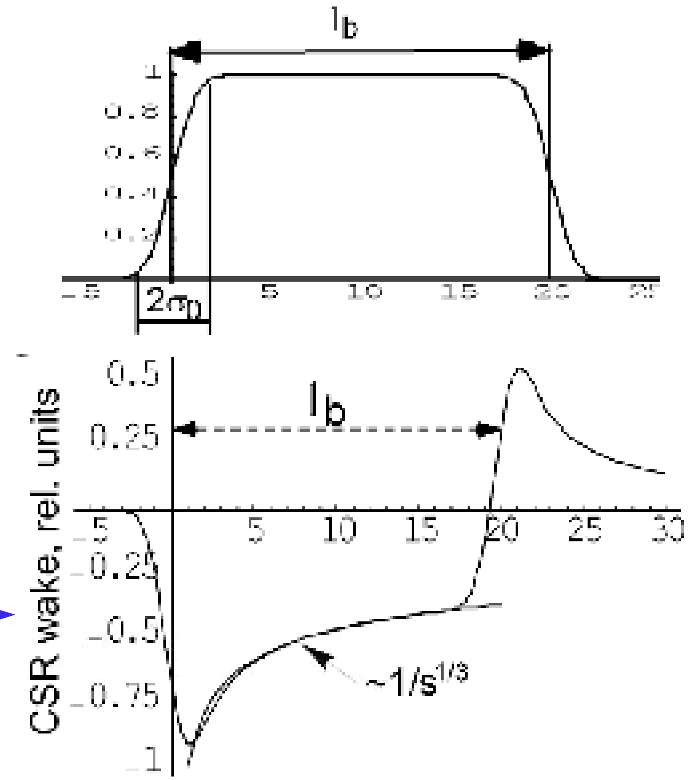
- Coherent synchrotron radiation
  - Electrons radiate coherently for □> 2 □ l_{bunch}
- Analytical model
- Traffic4 calculations





60° magnet with no shielding

Note head/tail reversed in plots



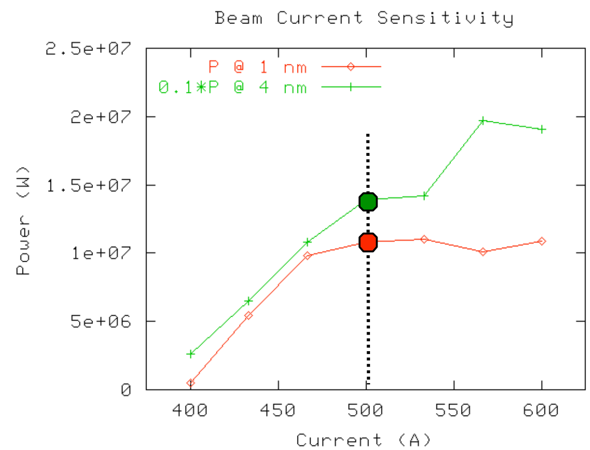
Energy loss along bunch following 180° bend. 120 MeV nominal energy, 7mm aperture in dipoles.

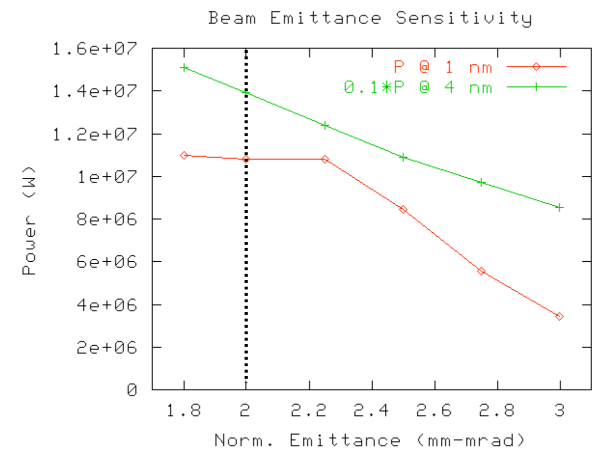
John Corlett, February 2003

4nm and 1nm output power sensitivity to input electron beam parameters

Base parameters:
500 Amps
200 keV uniform dE
2.0 mm-mrad
1.0 GW input P @240 nm
4-stage harmonic cascade
Time-steady simulations

Nominal output:
138 MW @ 4 nm
11 MW @ 1 nm





Note: 4-nm power scaled down 10X to fit on plots!